VOLUME IV
FLIGHT TEST MANAGEMENT

CHAPTER 6

SIMULATION FOR FLIGHT TEST

EXTRACT FROM MARCH 1982

USAF TEST PILOT SCHOOL
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6.1 INTRODUCTION

No engineering discipline has experienced such rapid growth as simulation. With the advent of modern digital computers the use of simulation has exploded. Simulation has become a critical part of U.S. research and development programs. Would the Space Shuttle even be possible without simulation ? Air Force contractors are relying more and more on simulation in the design and development process. It covers a wide spectrum of applications from the design and testing of aircraft and aircraft subsystems to the training of the aircrews. With further increases in electronic technology the applications for simulation will only be enhanced. The future objective of flight test may very well be the validation of math model simulations of aircraft and their subsystems. Test Pilots and Flight Test Engineers need an appreciation of this new and expanding field.

The flight test community is currently experiencing the twin problems of rapidly escalating test and energy costs coupled with increasing test requirements to satisfactorily evaluate systems of ever increasing complexibility. Simulation is viewed as a major contributor to the solution of this problem.

6.2 ARTICLES ON FLIGHT TEST SIMULATION

Attached are various articles from the previous years that deal with important facets of simulation to support flight test efforts. Enjoy your reading!

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SIMULATION AT THE DRYDEN FLIGHT RESEARCH FACILITY

John P. Smith*, Lawrence J. Schilling**, and Charles A. Wagner†
NASA Ames Research Center
Dryden Flight Research Facility
Edwards, California

Abstract

The Dryden Flight Research Facility has been a leader in developing simulation as an integral part of flight test research. This paper reviews the history of that effort, starting in 1957 and continuing to the present time. The contributions of the major program activities conducted at Dryden during this 25-year period to the development of a simulation philosophy and capability is explained.

Introduction

The Dryden Flight Research Facility has utilized simulation for support of flight research since 1957. During the late 1950's simulation was considered supplementary, but hardly essential, to flight programs. Predictions developed from the simulator and its contributions to flight results were questioned not only by pilots (who would rather fly airplanes), but also by many engineers.

Simulation at Dryden has developed over the past 25 years into an integral and essential part of the flight research program. Today pilots, as well as engineers, demand that simulation be included in the flight program. When the manager of one joint NASA/DOD program first learned the cost of a simulator, he asked, "What did you do before simulators?" The project pilot replied, "We named a lot of streets after pilots!" This statement reflects the most important value of simulation as it is practiced at Dryden: flight safety.

This paper reviews the history of simulation at Dryden, including the evolution of a simulation philosophy and the development of the laboratory appropriate to the type of flight research conducted at Dryden. The Dryden mission, which is to conduct research in flight, not in simulators, has greatly affected both the simulation philosophy and the resulting laboratory.

Before the X-15 Period

Before 1957 Dryden's experience with simulation was restricted to the use of other organizations' capabilities. The contribution of simulation to two programs that were conducted by members of the Dryden engineering staff during the period from 1955 to 1957 using a USAF simulator had a significant impact on the decision to acquire an in-house capability. In the first program a simulation using an analog computer led to an understanding of the roll coupling phenomenon, and during the second program simulation accurately predicted the X-2 lateral-directional control problem at Mach 3. The importance of these discoveries led Dryden to decide to acquire an analog computer capability. The X-2 experience in particular convinced the engineering staff that simulation had an important role to play in the future X-15 program.

In 1957 the resulting Dryden simulation laboratory consisted of one 48-amplifier analog computer and a cockpit simulator. The cockpit simulator consisted of an office chair, a simple spring-loaded control stick (Fig. 1), a 21-inch cathode ray tube (CRT) for pitch and roll angle presentation, and a maximum of three voltmeters with grease pencil markings to represent important cockpit instruments. This equipment was capable of solving the aircraft equations of motion for either five degrees of freedom (velocity and altitude constant), or three degrees of freedom (roll, yaw, and sideslip constant). Coefficients were required to be linear for the five-degree-of-freedom case, and they could vary only with Mach number for the three-degree-of-freedom solution. The principal uses of the simulator were experiment and system design and data reduction. Experiment design included studies to determine whether desired test conditions could be obtained, and it seldom involved the use of pilots. When a set of flight maneuvers was found which obtained the desired test conditions, a pilot would "fly" the simulator before the maneuver was incorporated into the flight plan. System design was limited to such tasks as evaluating the effectiveness of using velocity and attitude command (as compared to acceleration command) as reaction control system commands for the X-1B aircraft. The work in data reduction used the analog simulator as a tool to estimate aerodynamic coefficients based on flight data. The recorded flight control inputs were generated by a curve follower device and the programmed coefficients were adjusted until a reasonable match of the recorded flight maneuver was obtained.

Fig. 1 Early simulator control stick.

The Dryden simulation capability was expanded between 1957 and 1960: cockpits became more advanced and computer capability doubled. The cockpit displays included servo-driven attitude indicators and a simple center control stick with forces provided by a hydraulic system. Both the displays and the center stick

*Chief, Facilities Engineering Branch.
**Senior Simulation Engineer.
†Senior Electromechanical Engineer.

systems suffered from noise problems. The center stick would sometimes go into a hardover condition, which was of concern to anyone sitting in the cockpit seat. The expanded computer allowed, for the first time, the simplified simulation of an aircraft in six degrees of freedom. This capability was used to support the X-1B flight program. This was the first serious attempt to integrate a simulation into a flight program at Dryden. Unfortunately, the aircraft developed major problems which terminated the program before the value of the simulator could be demonstrated.

X-15 Period

From 1960 to 1968 the principal activity at Dryden that involved simulation was the X-15 program. This program more than any other established the simulation philosophy at Dryden. The simulator consisted of several large analog computers that were mechanized to solve the equations of motion (Fig. 2) and a fixed

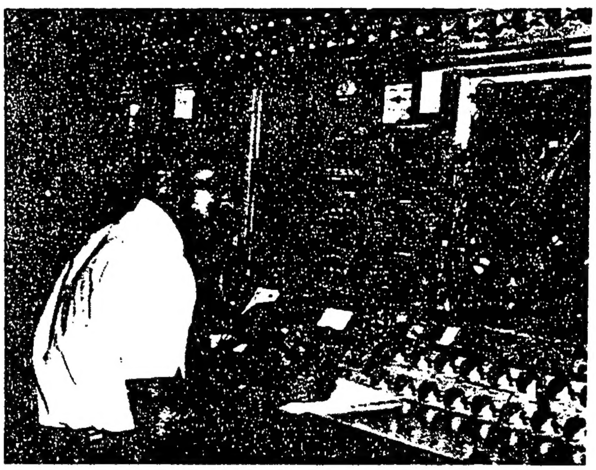

Fig. 2 X-15 analog computers.

base cockpit simulator and control system mockup (Fig. 3) which was developed by the builder of the X-15 aircraft. The control system mockup was used by the builder as a design tool for the definition of the X-15 control systems.

During the flight program the simulator was used primarily for flight planning and pilot training. The flight planner made a great deal of use of the simulator to determine the flight plan that best enabled the pilot to reach a particular test condition. After a flight plan was formulated, the pilot practiced the planned flight repeatedly. This permitted him to evaluate the proposed mission from the piloting standpoint and to recommend any modifications he felt necessary.

Because of the high risk nature of this program, the simulation of the X-15's aerodynamic characteristics was continually re-evaluated and corrected as the program progressed. For the first flight the simulator was programmed with the aerodynamic characteristics predicted from wind-tunnel tests and theory. After each envelope expansion flight the flight results were compared with the simulator predictions, differences were resolved, and the simulator was updated. As a result simulator performance became accurate, which significantly improved flight safety and contributed to pilot acceptance.

The validation of the simulator aerodynamic coefficients and the extrapolation of the coefficients into areas where the vehicle had not yet flown were of particular value. This approach allowed a comprehensive analysis of vehicle handling qualities at an early date and provided a basis for evaluating and resolving potential flight problems. For example, the X-15 simulator predicted that a reentry from an extremely high altitude could not be performed successfully if the stability augmentation system (SAS) malfunctioned. Simulator studies predicted that the removal of the lower rudder would permit successful piloted reentry from very high altitudes even if the augmentation failed. This configuration was tested in flight, and the results confirmed the simulator prediction.

The cockpit simulator and control system mockup for the X-15 were more sophisticated than any other simulation that had been used at Dryden. The cockpit was an exact duplicate of that of the X-15 (Fig. 4). The control system mockup included all of the vehicle linkages and cables, actuators, servos, hydraulic lines, hydraulic reservoir, and simulated control surfaces. Electronic breadboards of the stability augmentation and automatic control (MH-96) systems were provided.

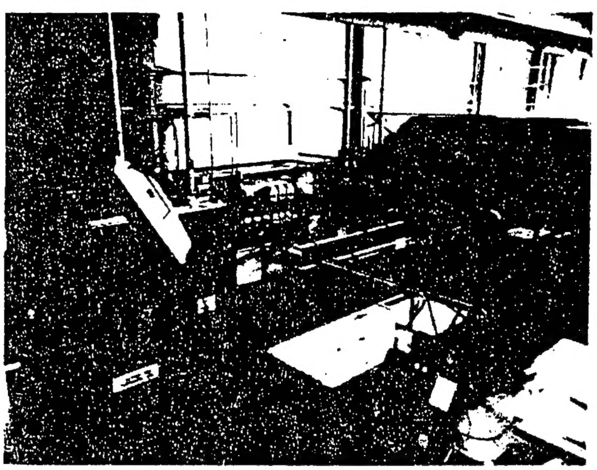

Fig. 3 X-15 cockpit simulator and control system mockup.

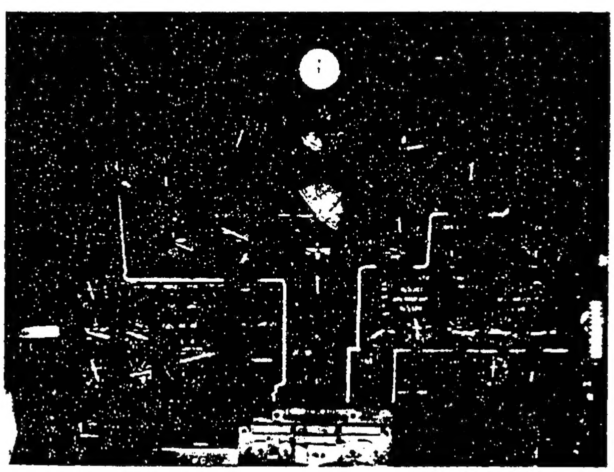

Fig. 4 X-15 cockpit simulator.

Experience gained during this program demonstrated the need to maintain an accurate representation of the aircraft cockpit for the programs conducted at Dryden. On one occasion, the instrument in the airplane was different from that in the simulator. In the simulator the pilot learned to check the panel for the position of the needle, instead of taking an actual reading, and since the position of the needle meant different things in the simulator and in flight, the desired test conditions were not obtained in flight. On another occasion the ballistic control system (BCS) on/off switch and the auxiliary power unit (APU) on/off switch were interchanged between the simulator and the airplane. It was normal procedure for the pilot to turn the BCS off after reentry. This was, of course, practiced on the simulator, as were all of the flight events. On one flight, the pilot caught himself reaching for the APU switch when he intended to shut down the BCS, an error that could have had serious consequences.

The control system mockup was initially intended to be a design tool for the SAS and MH-96 systems. X-15 numbers 1 and 2 were equipped with the SAS, and X-15 number 3 was equipped with the MH-96. The mockup was effective for its intended purpose. In addition, the mockup became a valuable facility for troubleshooting flight hardware problems. It was found to be a simple task to remove the flight control system boxes and interface them with the simulator. In this way the flight conditions where the problem occurred could be duplicated on the ground.

An event on a flight of the number 3 aircraft illustrates the use of the simulator in troubleshooting and correcting a flight problem. During reentry from high altitude, the pilot experienced an oscillation of the horizontal tail. This was detected as a low frequency rumble which rapidly increased in volume. The pilot switched the MH-96 system from the adaptive to the fixed gain mode, and the rumble went away. Analysis of the flight data indicated that a structural mode of the horizontal tail had been excited. To examine the cause of the problem, strain gages were installed on the mockup's simulated control surfaces. The strain gage outputs were combined with the computer-generated gyro signals and tied back into the MH-96. Simulator tests showed that the MH-96 had a gain peak at 13 Hz, which was close to the natural frequency of the horizontal tail. Once the horizontal tail was excited, the vibration was transmitted through the aircraft structure to the gyro package and then to the control system, which further excited the horizontal tail. The full potential of the problem was demonstrated when, during one of the simulator tests, the starboard simulated control surface separated from the mockup. The solution to the problem was the development of a 13 Hz notch filter, which was designed and verified using the simulator.

The simulator was found to be an excellent tool for preparing the pilot and mission control personnel for flight emergencies. Once this capability was recognized, it became normal practice for the pilot and engineering staff to war game those things that, if they went wrong in flight, might jeopardize the vehicle or the mission objectives. The simulator was modified to include a malfunction generator, which made it easier to simulate emergencies. The generator allowed the simulation of major and minor malfunctions. An example of a major malfunction which occurred during a flight early in the program with the XLR-11 engine illustrates the value of this capability. It was determined on the simulator that a premature shutdown of the engine at a particular point in the flight profile made it difficult for the vehicle to return to a landing site. If this malfunction occurred, the pilot had 2 seconds to initiate the proper maneuver. This emergency, which was practiced on the simulator, did occur in flight. The pilot initiated the proper maneuver, and the vehicle was recovered without incident. Minor malfunctions (those that jeopardized mission objectives) were also practiced. The use of the simulator so sharpened the pilots' abilities to cope with minor malfunctions, such as loss of cockpit indicators, that they became confident that they could complete an altitude mission with only the angle of attack indicator, altimeter, and cockpit timer.

The X-15 program also demonstrated that ground-based systems to simulate high g loads on the pilot during exit and reentry, cockpit motion cues, and high quality visual presentation of the outside world are not required at Dryden. This is consistent with the Dryden mission to conduct research in flight, not in a simulator. The experience and the engineering background of the pilots who participate in Dryden programs allow them to extrapolate the simulator experience to the flight environment without the help of these cues. Where physiological cues are necessary, in-flight or ground simulators at other sites are utilized.

By the end of the X-15 program simulation was established as an integral part of the flight program. The capabilities and events described in the preceding paragraphs contributed significantly to this. Other factors that were important in getting the pilots into the simulator were the limited amount of flight time available in the rocket engine vehicle and the highly competitive nature of the pilots. The following example illustrates the impact of these factors. Two pilots had the primary responsibility for making the high speed flights necessary to obtain heating information. This was a particularly difficult control task because of the high dynamic pressure, and it required a high level of pilot proficiency. One of the pilots spent as much time as he could get practicing the planned flights on the simulator. The other pilot only flew the simulator if he could not find anything else to do. The pilot who practiced extensively established a high percentage of data return, while the other pilot established a low percentage. This persuaded the poorer performing pilot to accept the simulator. He was the last pilot to accept simulation as an integral part of the flight program. After he was converted, it became normal for a pilot to spend 100 to 200 times as much clock time in the simulator as in actual flight.

Lifting Body Period

The lifting body program, which overlapped the X-15 program and lasted through the early 1970's, required the next major simulation activity. The program involved a series of vehicles, starting with a lightweight glider and concluding with three rocket airplanes. Although the program did not bring about any major changes in the use of simulation or the simulation philosophy developed during the X-15 program, it did result in the refinement of some of the approaches developed for the X-15, and it brought to the surface the need to make major changes in the simulation laboratory. It also marked the first exclusive use at Dryden of a simulator to design a flight control system.

Because of the nature of the lifting body design, the amount of flight time available to acquire data and to maintain pilot proficiency was even more limited than during the X-15 program. For example, each 3- to 4-minute HL-10 glide flight yielded about 2 minutes

of data time; each powered flight yielded about 5 minutes. In the first 37 flights only 3 hours, 25 minutes of total flight time and 2 hours, 20 minutes of data time were available. As a result, each flight had to be planned to utilize every available second. The extensive use of the simulator for flight planning enabled the performance, stability, control, hinge moments, and handling qualities of the HL-10 to be well documented from Mach 1.8 to landing over a 25° angle-of-attack range with this limited amount of data. The use of the simulator for pilot proficiency was very important in this program because of the very limited flight time. During the first 5 years of the program, the average number of flights per pilot per year was two.

One of the most difficult phases of the flight of a lifting body was the landing. This task required the initiation of the landing flare within a narrow time interval. Since these low-lift-to-drag-ratio vehicles were unpowered during landing, initiation of the flare too early would result in a potential stall before landing, whereas being late in the flare would result in a hard landing. This situation was examined on the simulator using a simple visual display device, and it resulted in the installation of a small solid propellent rocket as an emergency device for landing. The primary simulator for lifting body landings was an F-104 configured to approximate the lift-to-drag ratio of the lifting body in the landing configuration. The use of a flight vehicle to simulate the difficult landing task proved to be a very effective tool.

During the lifting body program it became clear that major changes in the simulation laboratory were needed. The X-15 utilized a dedicated simulator. The analog computer was programmed in 1960, and except for updates ot the aerodynamic coefficients, it remained essentially unchanged during the life of the program. There was more than one lifting body, and because of economic considerations not every vehicle could have its own dedicated analog computer. Therefore the analog computer had to be reprogrammed for each vehicle.

The computer simulations, which required a six-degree-of-freedom solution with nonlinear aerodynamic coefficients, were complex to set up, and it was difficult to verify correct operation. The time required to convert the simulation from one configuration to another was 1 week with overtime. This required that the flight program be conducted in such a way as to minimize the number of simulator changes. Since the majority of the time was needed to set up analog function generators and verify their performance, it was decided to acquire a digital computing system for function generation. Although a small digital computer was acquired during the X-15 program, this was the requirement that initiated the conversion of the simulation laboratory to the existing all-digital facility.

During the lifting body program, it was observed that the pilot felt that events occurred more quickly in flight than on the simulator. Experiments showed that running the simulator at 1.5 times real time represented a realistic representation of the flight environment to the pilot. Other programs have shown that this fast time factor appears to accurately represent the time frame of experimental flight.

The lifting body test period also resulted in the investigation of potential aerodynamic uncertainties for purposes of planning the first flight of each new vehicle. The errors in the aerodynamic coefficients that were thought possible on the basis of experience were evaluated and mechanized on the simulator. This technique was very successful in predicting the range of control problems that might occur in flight. The mechanization and investigation of these uncertainties are now a standard feature of Dryden flight programs.

After the Lifting Body

After the lifting body program the simulation environment at Dryden changed significantly. The programs involved not experimental aircraft, but rather modified conventional aircraft. These programs did not require the extensive simulation necessary to evaluate a new vehicle's full mission capability, but rather a simpler simulation aimed at particular test conditions. This resulted in increasing numbers of simulations, shorter program lifetimes, and decreasing lead times (the time available for developing the simulations). Although these simulations did not require full mission capability, they did have to be high fidelity.

This period also marked the start of the digital flight control system programs. The first program supported was the F-8 digital fly-by-wire. The standard F-8 mechanical system was removed and surplus Apollo guidance system components and a lunar module guidance computer were installed. An "iron bird" was assembled and interfaced with the simulation computers. The iron bird was a modified F-8 with the digital flight systems installed. This was the first time that non-analog aircraft systems were either simulated or interfaced at Dryden.

The need to support an increased variety and number of simulations, simulate and interface with digital rather than analog flight systems, and the reduced lead time to develop a simualtion led to the conversion to an all-digital facility and the development of modular reusable cockpits and specialized interface equipment. It became apparent that few programs could justify or afford a dedicated cockpit simulator, and that the simulation facility would have to be standardized to deal with a number of programs effectively.

The first attempt at a standardized computer program was called ICARUS. The name was chosen to caution the engineer about the use of this approach. ICARUS was a generalized digital simulation program. The program included the six-degree-of-freedom equations of motion with the capability of a number of undefined control terms and aerodynamic coefficients. The program defined the number of coefficients that could be a function of one, two, or three variables. The engineer was required to specify the aerodynamic data to be used within the constraints of ICARUS. The engineer could elect to use the linear control system provided by ICARUS or program some other transfer function.

ICARUS was a highly successful first step in the development of a standard software system. The initial uses of the system demonstrated that a simple six-degree-of-freedom simulation program could be assembled and checked out within 1 week. This approach has been extended in recent years to a more advanced software library system using high level software languages. The major factors in establishing a simulation at Dryden are the definition of the aerodynamic models, the programming of the control system, and (in the case of systems aircraft) the interface or simulation of those systems. The use of generalized software systems using high level languages has enabled

Dryden to support today's workload, which is several times greater than it was in 1970, with half the number of simulation engineers.

Current simulation philosophy at Dryden stresses convenient user interfaces. Complete control of the simulation from the cockpit station is provided through control boxes and a remote CRT. The CRT provides displays which have been tailored to a project's requirements to provide all data of interest. These displays are dynamically refreshed at high rate during operation. The control boxes provide many functions at the push of a button and are also tailored to project needs. Standard functions include autotrim, initial condition control, initial condition capture, and mode and gain control interfaces for the aircraft control system. If the initial condition capture feature has been selected, the vehicle's state vector is stored upon request, allowing the simulation to return to the stored condition whenever desired. The tools combine to improve user productivity and reduce support requirements. Simulation sessions can be and are productively conducted by one individual in many cases.

With the development of digital computer simulation programs, it became possible to restore a simulation easily. Whereas it took 1 week to restore a lifting body on an analog computer, a program of similar complexity could be restored on a digital computer in a few minutes. Where the analog computer might give a range of results for given inputs, the digital computer would produce consistent results every time, if loaded correctly. The limiting factor on changing a simulation then became the simulator cockpit.

In 1970, Dryden's simulation laboratory set a goal of being able to completely reconfigure a cockpit simulator in 30 minutes. This required the development of a general purpose cockpit shell and wiring system (Fig. 5) that could accept a wide range of cockpit side

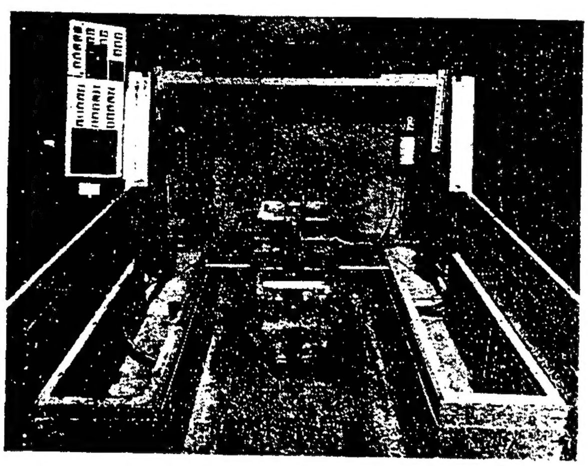

Fig. 5 Simulator cockpit shell.

panels, controls, and instrument panels. The resulting cockpit shell (Figs. 6 and 7) can be used for a wide range of simulation programs. The biggest problem in meeting a 30-minute reconfiguration requirement was the cockpit control system. Up to that time, most simulations at Dryden used spring-loaded force systems, while such simulations as the X-15 and F-8 digital fly-by-wire used hydraulic systems. The answer was found in the dc torque motor-driven elec-

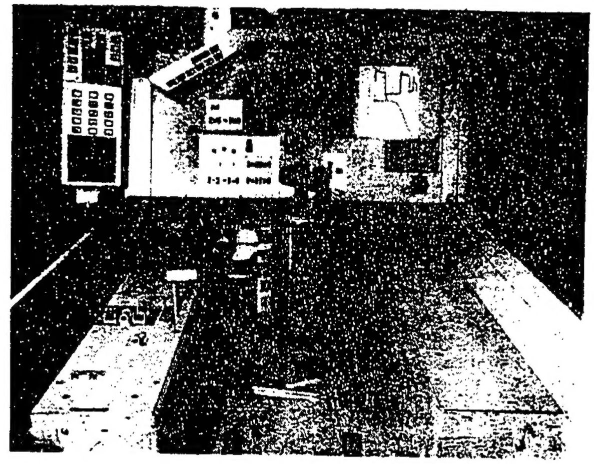

Fig. 6 Cockpit configuration A.

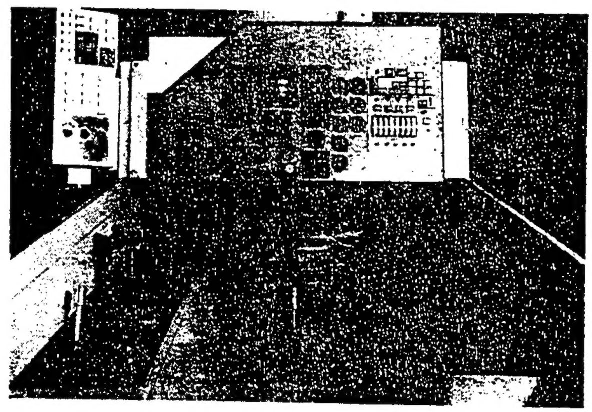

Fig. 7 Cockpit configuration B.

tric stick. This system (Fig. 8), which was invented by two Dryden engineers and is programmed by a

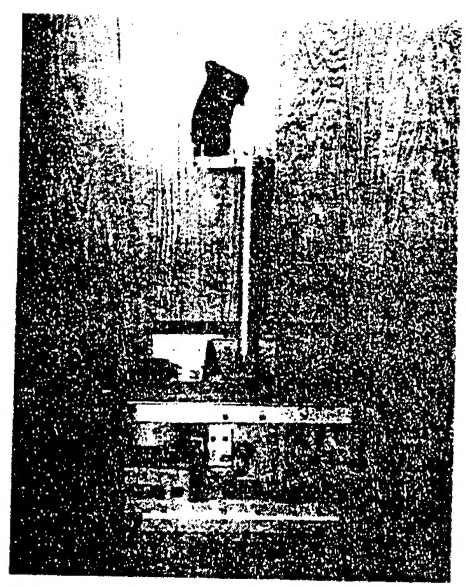

Fig. 8 Electric stick.

specially designed analog computer, enabled the reconfiguration requirements to be met. The electric stick provides a wide range of capabilities (Table 1).

Table 1 - Electric Stick Characteristics

	Pitch stick	Roll stick	Rudder pedals
Maximum force, lb	60	52	153
Total travel range, in.	16	13.4	9.6
Absolute maximum force gradient, lb/in.	80	50	560
Maximum velocity, in/sec	64	75	26
Maximum programmable gradient, lb/in.	10.6	11.8	67
Maximum programmable breakout, lb	16.9	14.5	42
Maximum programmable friction, lb	11	9.8	28
Size of stick assembly, excluding stick shaft, in.	27.5 X 19 X 15 high		
Size of rudder pedal assembly, in.	19 X 25 X 13.3 high		
Weigh of stick assembly, lb	150		
Weight of rudder pedal assembly, lb	97		
Electrical power consumption, idle, KVA	0.66		
Electrical power consumption, maximum, KVA	2.64		

Programmable variables in each axis:
- Travel limits (hard stops), independent in each direction
- Trim travel limits, independent in each direction
- Linear force gradient
- Damping
- Breakout force
- Trim rate
- Friction
- Mass
- Initial trim position

The trim function can be switched from parallel trim, where the stick moves with the trim position, to series trim, where the stick is stationary.

The reconfiguration time has been reduced to less than 20 minutes. Through the use of three general purpose cockpit stations, the facility supports virtually uninterrupted simulation 10 or more hours per day, with sessions usually lasting 2 hours.

The modular cockpit and electric stick have been strongly endorsed by pilots who have used simulators at Dryden. When Dryden developed its remotely piloted research vehicle (RPRV) laboratory, the pilots requested that the simulation cockpit systems be utilized. Pilots who have come in contact with the Dryden capability have been impressed. The chief pilot of a major airframe contractor, who was not known to be a simulation proponent, flew a Dryden simulation of one of his company's airplanes as part of a joint NASA/DOD program. Later, when he was going to conduct a test program at his facility on that airplane, he flew 3000 miles to get time on the Dryden simulator.

Remotely Piloted Research Vehicle and Systems Aircraft Period

The current period at Dryden involves significant simulation requirements for remotely piloted research vehicles and systems aircraft. This period draws upon the technology developed over the 25 years that simulation has been used at Dryden. Simulation today performs the full range of functions that have been described in this paper. A significant additional requirement of simulation in this period is the development, validation, and verification of flight software. As a result, the percentage of piloted simulations in many programs has decreased. Typical of programs with heavy systems requirements is the highly maneuverable aircraft technology (HiMAT) program. Before the first flight, 2200 hours were spent in simulation activity, of which only 125 hours were piloted. On the other end of the spectrum, an effort to develop remotely computed displays involves pilot participation almost 100 percent of the time.

The complexity of today's systems aircraft, some of which are also RPRV's, is so great that attempting to develop them without a simulator would be futile. The HiMAT project at Dryden has been one of the major users of this type of simulation. This program used a hierarchy of simulations, ranging from an all-computer synthesis of the vehicle systems to providing the interface with the flight vehicle (Fig. 9). For systems aircraft, simulation is the principal tool in the design, development, validation, verification, flight certification and troubleshooting for the systems.

Software development, validation, and verification requirements for RPRV's have resulted in the use of identical control law computers for both simulation and flight. Special interface equipment has been developed which makes the simulation control law computers perform as if they were interfacing with flight systems rather than with simulation computers and simulated flight hardware. In this way, the flight code is exercised the same in simulation as it is in flight. As a result, the certification of the flight software can take place predominantly in the simulation laboratory. Before an RPRV flight, a copy of the control law computer code is transferred from the simulation laboratory to the flight system control law computer.

The interchangeability of software between the simulation and flight systems, which was developed to satisfy the software development, validation, and verification requirement, is a key capability for today's programs. The development of cockpit display algorithms is another example of the application of this capability. Display algorithms are developed on the simulator to assist the pilot in obtaining a desired test condition. The software interchangeability allows the direct transfer of these algorithms to the flight system. The use of simulator-developed display algorithms has allowed Dryden to duplicate flight test conditions to the accuracy of a mechanical fixture in a wind tunnel.

Future Directions

Several significant changes are planned in the Dryden simulation laboratory. A new generation of digital computers will be acquired that can execute a frame of simulation software in less than 10 ms. The software will be written a high level language, such as FORTRAN. This improved capability will permit accurate simulations of high-frequency aircraft phenomena. It will also further increase the productivity of simulation engineers by reducing or eliminating the few programming tasks that must be done in assembly language.

Other planned changes include the conversion of all signal distribution systems from analog to digital. This change will provide three major advantages. First, signal quality will improve significantly, particularly where signals must travel great distances. Second, far fewer cables will be required to connect a simulation cockpit or an airplane to a simulation computer. Third, much of the work required to reconfigure a cockpit from one aircraft to another will be automated. The existing 20 minute time requirement will be reduced to less than 10 minutes. Human errors in making electrical adjustments will be virtually eliminated. The only remaining tasks will be physically installing the correct instrument and side console panels and loading the computer program.

The analog computer that controls the cockpit stick and rudder pedals will be completely redesigned. Some of the planned enhancements include incorporating programmable nonlinear force functions within the computer. All setups will be done automatically under simulation computer control. Stick character-

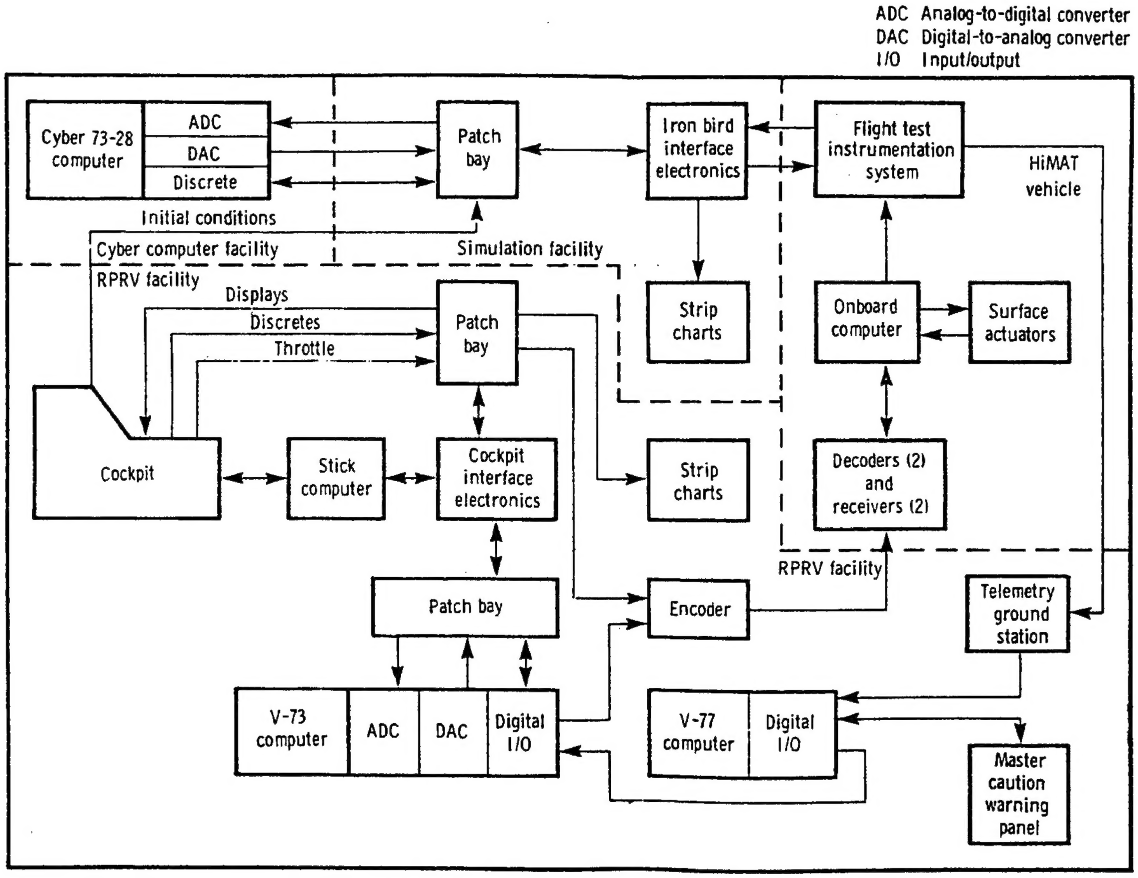

Fig. 9 HiMAT hierarchy of simulation.

istics will be controllable in real time by the simulation computer, enabling accurate simulation of force feel characteristics that vary with flight conditions.

These planned changes in Dryden's simulation laboratory represent the next step in an ongoing effort. This effort has several goals. Personnel productivity will continue to be increased. The laboratory will continue to become more flexible. As aircraft systems become more complex, the laboratory will maintain the capability to model, test, and verify those systems. We expect that simulation will continue to be one of the most significant tools in our flight test inventory.

Systems aircraft will be the major driver for the future simulation capability at Dryden. Simulation will not only be an integral part of the flight program but will also be a critical element of the flight system. In the successful programs of the future, simulation will provide the bridge, and safety net, from the concept to the flight system and vehicle.

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THE USE OF ENGINEERING SIMULATION TO SUPPORT AIRCRAFT FLIGHT TESTING AT THE U.S. AIR FORCE FLIGHT TEST CENTER

by

Richard A. Wood
Chief, Flight Test Simulation Branch
U.S. Air Force Flight Test Center
Edwards Air Force Base, California

Abstract

The engineering simulator has become an integral part of the flight test tools to analyze flight test results and increase the knowledge gained from the flight tests themselves. The test team has been forced to closely scrutinize their weapon system and the spectrum of possible tests to determine the minimum tests required, determine the most important tests to fly, and to get the most from each flight hour. The engineering simulator provides an inexpensive means to closely scrutinize the weapon system and the proposed test plan. The U.S. Air Force Flight Test Center has successfully used the engineering simulator to educate test personnel, determine flight test envelopes, optimize test plans, enhance command and control procedures, develop modifications to flight control systems, investigate unexpected test results, investigate accidents, develop math models for training simulators, and provide practice flying for test pilots. Aircraft simulated have included the Space Shuttle, X-2, Dynasoar, lifting bodies, SR-71, C-133, A-7, F-5, F-15, F-16, and AFTI/F-16.

Introduction

The catch phrase in the Air Force test business these days is "test smarter". What test smarter really means is more for your money, greater efficiency, more information per flight hour. The emphasis on greater efficiency is forcing test managers to insist on fewer repeat tests and to obtain only the data required. This paper is about how the Air Force Flight Test Center (AFFTC) uses aircraft simulation to get the most from the flight test dollar.

At the AFFTC, the simulator is considered a teaching aid. The motto:

Learn before flight test

Learn the most from flight test

has been adopted. It has been said "the purpose of computing is insight, not numbers". The simulator is a tool that provides the test team with some insight into how and why their aircraft works the way it does.

History

The simulation facility began in 1954, simulating such aircraft as the X-2 and the Dynasoar. Over the years, over two dozen aircraft have been simulated for a large variety of purposes. The facility began with analog computers, evolved into a hybrid system, and in 1979 was refurbished into a completely digital facility. Table 1 lists some of the major projects and the analysis they accomplished using the simulator.

Facilities

The AFFTC simulation facility has four computer systems and four cockpits available. Three cockpits are fixed based and one is a moving base. All cockpits are fabricated, modified, and maintained in-house. The cockpits can be modified to satisfy any project's particular needs. A single CRT visual display is available. The CRT can be used on any of the fixed base cockpits.

The computer facilities consist of:

a) Perkin-Elmer 8/32

b) SEL 32/55

c) AD 10/PDP 11 Complex

d) EAI 2000

The Perkin-Elmer and SEL machines are the primary machines; handling 98 percent of the work load (Table 2).

In most cases two simulations can be run on the Perkin-Elmer machine simultaneously. One simulation at a time can be run on the SEL machine. Therefore, it is possible to be operating three simulations and have engineers doing batch processing all simultaneously.

However, in some cases a single simulation can be so large (i.e., requires most of the computation capability) that only one simulation can be run on the Perkin-Elmer machine. The AFTI/F-16 has succeeded in doing this. Most simulations require no more than two CPUs and run with frame times of 20 or 40 milliseconds. The AFTI/F-16, however, uses four CPUs and runs with a frame time of 15.6 milliseconds.

Four cockpits are available, three fixed base and one motion base. The fixed based cockpits include an AFTI/F-16, Space Shuttle, and a generic fighter. The motion base simulator is currently configured similar to an F-16 instrument panel but with a center stick. It can be used for any type aircraft, including side-by-side seating with yoke and column.

Flight Test Simulation

Why simulate, and why is simulation more important as a flight test tool today than yesterday? Basically, three major factors have changed the flight test scene.

First, back in the "good-old" days, aircraft had simple flight control systems; cables, springs, simple actuators. It was easy to understand how the control system worked. The actuator was connected directly to the stick and when the stick

moved, the surface followed. Today aircraft have high authority stability and control augmentation systems with numerous feedback loops. An engineer can no longer understand how the control system, aerodynamics, and pilot will all interact simply by looking at block diagrams. Computers fly airplanes today, and the stick is merely a command lever for the computer. An engineer must do more than look at block diagrams to understand these systems. That "something more" is to build and fly a simulation.

Second, back in the good-old days, testers were concerned with testing the aircraft as a separate entity. That is, without considering the pilot as an integral part of the control system. By comparing an aircraft to a set of specifications they hoped to determine if it followed the recipe for a good aircraft. The tests were open loop, highly quantitative; pitch pulses and steady heading sideslips and the like. Today the pilot is recognized as an integral part of the feedback control system and testers are more concerned with operationally oriented testing. There is more concern with pilot work load and pilot transfer functions. In other words, how does the total system (pilot, control system, and aerodynamics) operate as a whole in a high gain situation; like when you are at low altitude, high speed, monitoring aircraft systems, looking for your target, and looking for the bad guys that are shooting at you.

Third, money; flight test projects are more expensive than previously. The simulator, in some cases, has permitted a 50 percent reduction in flight time.

For the engineer to understand his weapon system, for the engineer to gain some insight into how all this will work in a high-pilot-gain situation, he needs a tool that duplicates the real-life environment as much as possible. Aircraft designers make extensive use of simulation in some form during the design process. If the designer needs a simulator in order to understand and optimize his aircraft, what makes the flight test engineer think he can understand the system without using a simulator?

At the AFFTC, the flight test engineer is also the aerodynamicist and analyst. Those work tasks are not segregated. The engineer not only flies the tests, he also oversees the data processing, analyzes results, and reports on the completed tests and completed analysis.

If the flight test engineer is to:

a) understand how the control system works at the aerodynamic limits of the aircraft,

b) understand how the aircraft will respond when the flight control system is at its limits of performance,

c) design a test plan that fully exercises the system throughout the flight envelope safely and efficiently,

d) analyze unexpected flight test results, he is going to have to be very perceptive or make use of a simulator.

Education

The act of "building" a simulation forces the engineer to become very intimate with the aerodynamics and flight control system. An engineer cannot build a simulation without knowing a lot about his aircraft. By the time the simulation is built and checked out, the engineer has learned the effect of each stability derivative, and purpose and authority of every component in the control system. Even if the simulator is never flown the engineer has learned the intimate details of his aircraft.

Rehearse Flights

The second major use of the simulation facility is to rehearse flights. As in many situations practice makes perfect. The AFTI/F-16 Test Force estimates that they obtain 30 percent more useable data per flight by practicing each flight on the simulator. The improvement comes about as a result of the pilot and each engineer knowing exactly what to expect, knowing exactly who is going to be responsible for what, perfecting the pilot-to-ground-station communications, insuring the pilot understands the control input required to obtain the test data. In other words, it serves as a "super" pre-flight briefing; much better than sitting around a conference room table talking about the flight cards. Any inefficiencies in the flight plan or misunderstandings are readily recognized during the practice flight. During the actual aircraft flight fewer test points need to be repeated. When a repeat is necessary, a minimum of explanation is required. The time required for the engineers to evaluate the last maneuver (and clear the pilot to proceed with the next maneuver) is minimized because the engineers know exactly what response they should be seeing in the critical parameters.

The earliest and most avid users of the simulation facility were the engineers working on the X-series aircraft and lifting body vehicles. These fellows were taking giant steps forward to expand the known flight envelope with aircraft of radically new design. They also were faced with relatively short flights and relatively few flights. The aircraft were not flown twice a day, five days a week, as we sometimes do with A-10s and F-16s. They had to get the most out of their flight time and they had to understand as much as possible about the flight envelope before they flew. As a result, the simulator became a mandatory tool for the flight test engineer. That kind of utilization of the simulator is still with us and will continue to grow even for relatively conventional flight test projects.

Parametric Studies

The third major use of the simulator is to investigate or analyze:

a) changes to the control system

b) unexpected test results

c) hazardous or unusual flight conditions.

It is uneconomical and sometimes hazardous to investigate unexpected or unusual test results in the aircraft. The simulator gives the test team the ability to quickly try new control components, or repeat hazardous test conditions while observing any parameter. Very seldom does the test team have the opportunity to add new instrumentation in the middle of a test project. But, on the simulator any parameter can be called to the output queue in a matter of seconds.

The net result of utilizing the simulator in these three major areas is a tremendous amount of insight. It makes the entire test plan and test team more efficient. The testers learn where to spend most of their time testing and analyzing. They learn what the benign test conditions are and what the critical test conditions are. They learn what causes problems or unexpected test results; with emphasis on causes. They gain the insight to make better recommendations on improving the aircraft. It enhances the safety, as well as the efficiency, of test operations by improving their ability to make good decisions, in real-time, during hazardous flight tests.

Case Histories

C-133 Fixed Prop Pitch

When the Air Force was still flying C-133s, a problem was encountered with the variable propeller pitch mechanism. In simple terms, there was a failure mode that resulted in all props locking at whatever pitch they had at the moment of failure. In this failure mode, the characteristics of the fuel control mechanism were such that if the engine speed dropped below 88 percent the engine no longer responded to throttle commands. As you might expect, this situation made it difficult to land the aircraft.

The task given the Test Center was to develop a landing pattern for C-133s with fixed propeller pitch and fixed throttle. Obviously there was a large range of pitch-angle that the props could lock at. This combined with the range of available flap settings and descent profiles resulted in a large matrix of possible emergency procedures and landing patterns. It clearly was not safe nor efficient to flight test every possible combination.

The approach to the problem was as follows:

1) determine which prop-pitch failure conditions were most critical

2) determine which emergency procedures were clearly unacceptable and which showed the highest probability of success

3) flight test the most critical failures with the emergency procedures and landing patterns that showed the best chance for a successful landing.

Steps 1 and 2 were conducted on the simulator, step 3 with actual aircraft flight tests.

The simulator provided the opportunity to investigate a large matrix of conditions quickly, cheaply, and safely. With aircraft position displayed on an X-Y plotter and important parameters displayed on strip chart recorders, IFR approaches were flown with a "controller" talking the pilot down. Under these conditions, in a matter of days, the most critical failures and most probable recovery techniques were identified. The flight test program then investigated a relatively small matrix of failure conditions and recovery techniques. This short flight test program was able to determine an easy recovery technique that would be acceptable under all the critical failure conditions.

A-7D Pure Yaw Departure

The A-7 aircraft is normally considered to depart with a relatively large rolling motion and relatively little yawing motion. A few years ago an A-7 departed in a pure yaw departure with no roll motion. The pilot reported that while applying normal control inputs to recover from a high angle-of-attack he experienced a very large sideslip and yaw rate without the usual rolling motion. The aircraft eventually yawed off into a spin.

It obviously being too hazardous and too expensive to conduct a departure-spin flight test program, the Test Center was asked to evaluate this unusual departure mode. An analysis of stability and control derivatives was insufficient to determine the feasibility of the reported departure. A real-time simulation was required to evaluate the effects of control inputs just prior to the departure. The maneuver that resulted in the aircraft departure was flown on the simulator. If normal recovery procedures were vigorously followed, no departure occurred. However, about 10 percent of the time if the pilot timed his aileron input just right, the aircraft would yaw to about 50 degrees sideslip with no roll motion and then continue into a spin. The simulation showed that with just the right control input a pilot could counteract the normal dihedral effect and allow the aircraft to develop a large yaw rate (and sideslip angle) with no rolling motion. Once the yaw rate was established it was impossible to stop it.

The simulator provided a safe and efficient tool to confirm what the pilot had reported. Without the simulator it is most probable the pilots comments alone would not have been sufficient, to convince people that this departure mode was possible.

F-5F and F-15 High Angle-of-Attack Tests

The high angle-of-attack, departure, and spin testing of fighter aircraft requires a large test matrix and is rather time consuming. The procedure is to start with simple 1-g stalls then gradually build up to more violent maneuvers; stalls with normal and moderate control inputs, stalls with large and vigorous control inputs, and finally aggressive maneuvers with multiple control inputs and pro-spin control inputs. The hazardous nature of the test requires a very methodical technique. Fortunately, many modern fighters are quite spin resistant, which means many of the preliminary steps in the spin testing are benign.

In the case of the F-15, the simulator was used to eliminate those maneuvers which clearly would not cause a departure and to determine what control inputs most probably would cause a departure. Thus saving considerable flight time.

The F-5F project took this procedure one step further by determining, on the simulator, what the angles-of-attack and sideslip boundaries for controlled flight were.

Each maneuver was flown on the simulator. Benign test conditions were eliminated from the flight test plan and the trends of controllability were watched closely. At the beginning of the actual flight test careful comparisons were made between simulator and aircraft. Once the accuracy of the simulation was established numerous build-up points were eliminated from the flight tests. The airplane was flown up to the predicted boundaries of controllability. If the aircraft reacted similar to the simulation, flight tests were terminated at that point.

The F-5F project estimated that they flew only half the number of flights they otherwise would have needed. Using the simulator in this fashion probably prevented them from departing the aircraft on several occasions. An experience of this nature clearly points out the cost effectiveness of a simulator.

YF-16 Control System Development

The YF-16 aircraft went through a fairly extensive control system optimization. The nature of a computer controlled fly-by-wire system allows frequent and rapid modifications to be made. Flight safety requires that changes to the control system be fully checked out on the ground before they are flown for the first time.

The simulation was constructed such that the aircraft's flight control computer could be connected directly to the simulator. After modifying the computer, but before actually flying it in the aircraft, the control box was flown on the simulator. This gave the test team an opportunity to check that the modification gave the desired effect, as well as checking that the box was still working correctly.

Having the simulator available for this purpose saved substantial time and allowed one-day turn around every time a flight control system change was made. It also gave the test team confidence that the modfication did not adversely affect the overall operation of the flight control system. That confidence allowed them to move directly into evaluation tests, without first performing excessive safety checks.

YF-16 Inadvertent Departure

Regardless of how complete your preparations are, occasionally you get surprised by unexpected test results. During the YF-16 tests the aircraft departed controlled flight under circumstances previously thought to be benign. It would have been too hazardous to repeat the maneuver without an anti-spin chute installed, and it would have been too time consuming and costly to install one at that point in the project.

Instead, the test team flew the maneuver on the simulator. They were able to repeat the maneuver numerous times. What they found was that under these particular circumstances the horizontal tail was hardover due to saturated feedback signals. With the tail already against a stop, the angle-of-attack limiting features of the control system could do no good.

An obvious advantage of the simulator, in this situation, is that any signal anywhere in the control system can be recorded and monitored. On an aircraft with hardwired instrumentation, it is not practical to add new instrumentation half-way through the test project. But with the simulator, the test team was able to determine the magnitude of every signal going to the actuator and thereby pinpoint the exact cause of the problem.

AFTI/F-16 Structural Limits

The AFTI/F-16 test team also got surprised on a test flight and exceeded a structural limit on the vertical tail during a flat turn maneuver. A quick analysis of the flight test results indicated that the control system was not operating as intended.

Within 24 hours of the actual incident the test team had repeated the maneuver on the simulator, isolated the control component which allowed the overshoot, and had a recommended fix established. But, perhaps most important of all, the test team acquired complete understanding of the cause of the problem. The insight into the problem gave the test team the knowledge they needed to avoid repeating the incident. As a result they could resume flying the aircraft immediately. If the test team did not have the simulator available to them it would have been many days or weeks before they could have isolated the cause and probable fix. Once again, the inherent capability to monitor any signal within the control system and to quickly change transfer functions proved the simulator's worth as a flight test tool.

F-15 Aileron-Rudder Interconnect

During the F-15 development flight test project, the pilots complained of sluggish directional response in high gain tracking tasks. The cause of the problem was not immediately apparent by analyzing the flight test results.

Similar tasks were flown on the simulator. The simulator had a better response than the aircraft. Comparison of simulator test results and aircraft test results showed the aircraft had a larger hysteresis in the aileron-rudder interconnect (ARI) than the simulator.

Revision of the interconnect's hardware components was not practical, even though that would have been the technically cleanest solution. The simulator study was continued to see what could be done in the flight control computer to alleviate the problem. Hysteresis was added to the simulation to match the aircraft. The study showed that by making a relatively simple change to the ARI gain the problem was alleviated. The hysteresis did not go away, but the change in gain provided enough rudder deflection to speed up the directional response in a typical tracking task.

The utility of having a simulator at the test site was demonstrated. The test pilots and engineers could use it in a timely fashion. The people

flying the tests and analyzing the data were readily available to participate in the simulator study. Thereby providing the fastest possible assessment of the problem and the fix. The net result was that the development program was able to continue with a minimum of delays.

SR-71 Minimum Control Speed

The SR-71 aircraft has a very large operational weight range, a very large asymmetric thrust moment with the loss of one engine, and a fairly long engine spool down time. With the large amount of excess thrust available, even on one engine, it is possible for the aircraft to lose an engine below the static minimum control speed and accelerate to a speed faster than minimum control and only suffer a momentary loss of directional control. The circumstances were such that during takeoff the effective minimum control speed in the dynamic situation was significantly different than the classical static minimum control speed.

Part of the test team's job was to document this situation. It was determined that the large matrix of test points made it impractical to do a complete minimum control speed flight test program. The solution was to put the aircraft on a simulator, analyze the dynamic minimum control speed over the full range of weight and thrust, and determine the most critical set of conditions. A relatively few flight tests were conducted to confirm the accuracy of the simulation and to demonstrate the most critical conditions. However, it was not practical to demonstrate the single most critical condition, that of sea level thrust. However, the simulation's accuracy had been sufficiently proven and the simulator was used to determine the minimum control speed with sea level thrust.

Summary

These are just a few examples of utilizing a simulator to support flight test efforts. The entire list is far too long to include here. The important point is that almost every flight test project can make some use of a simulator. All projects will not use the simulator for all things. A simulator like any other tool has an appropriate use in some situations. But, almost all flight test projects, sooner or later, come across a situation where a simulator will significantly enhance their operation's safety, efficiency, or both. Having that simulation at the test site minimizes the time required to conduct the simulation study and maximizes the involvement of the test personnel in the study.

Abbreviations

AFFTC	Air Force Flight Test Center
AOA	angle of attack
CPU	central processing unit
CRT	cathode ray tube
DOF	degrees of freedom
FCS	flight control system
Kb	kilo byte
Mb	mega byte
PIO	pilot induced oscillation
RCS	reaction control system

Table 1 Some typical AFFTC flight test simulations

Project	Date	Utilization
X-20A Dynasoar Analog 6 DOF	1959-1963	Flight Planning Cockpit Evaluation Handling Qualities and Energy Management Studies
X-15A-2 Hybrid 6 DOF	1964-1969	Flight Planning Pilot Training (Backup) Real-Time Heating Handling Qualities and Energy Management Studies
F-104 Strake Analog 5 DOF	1964	Stick Kicker Boundary Test Technique
NF-104 Analog 5 DOF	1964-1966	Handling Qualities Low Speed RCS Kicker Design Accident Investigation Engine Gyroscopic Effects Drag Chute Spin Recovery Student Training Concepts
Analog 3 DOF		Optimum Zoom Profile Optimum Accel Profile Flight Planning Pilot Training (Limited) Parametric Studies (Wind, Weight, etc.) Placards for Students Student Training Concepts
M2-F2 Hybrid 6 DOF	1965-1966	Glide Flight Planning FCS Design Optimization FCS Failure Analysis Launch Characteristics Trim Changes Handling Qualities All Pilot Training Powered Flight Planning
SR-71 Hybrid 6 DOF	1965-1969	Handling Qualities Survey Flight Planning Performance (Engine) Minimum Control Speed Single Engine Performance Engine Failure at Cruise Longitudinal Stability at Cruise Accident Investigation
X-24A Hybrid 6 DOF	1969-1971	Performance Envelope Definition Handling Qualities Envelope Definition Launch Characteristics Envelope Expansion Flight Planning Emergency Procedures Pilot Training Operational Flight Support FCS Design Optimization Test Maneuver Development
X-24B Hybrid 6 DOF	1971-1975	FCS Design Aerodynamic Design Other Same as X-24A
A7 Lowspeed Analog 5 DOF	Feb 1972	Accident Investigation Departure Characteristics Digitac FCS Validation
F-15 Analog 5 DOF	1974	Handling Qualities Survey Departure Characteristics
F-5F Digital		Test Maneuver Development Departure Characteristics

Table 1 (Continued)

Project	Date	Utilization
YF-16 Analog 5, Limited 6 DOF	1974-1975	FCS Development Handling Qualities Survey High AOA Evaluation Departure Characteristics Test Maneuver Development Missile Flutter
Space Shuttle Hybrid 6 DOF	1976-1978	Low Speed Handling Qualities Survey Energy Management Test Maneuver Development Tailcone-off Flight Plan PIO Evaluation
Space Shuttle Hybrid 6 DOF Digital 6 DOF	1977-Present	Re-entry Handling Qualities Survey Entry Cross Range Capability FCS/Guidance Evaluation Aero Heating Evaluation Thermal Protection System Capability FCS Design Optimization Test Maneuver Development Auxiliary Power Unit Fuel Consumption Hydraulic System Management RCS Fuel Consumption
AFTI/F-16 Digital	1980-Present	FCS Development Test Maneuver Development Pilot Training Test Planning
Test Pilot School F-16A Digital	1981-Present	Student Projects
ASAT Digital	Present	Missile Separation Dynamics
F-15 Digital	Present	Test Maneuver Development Departure Characteristics

Table 2 Computer facilities

	Number of CPUs	Memory Per CPU	Shared Memory	Number of Disc Drives	Size Of Disc Drives
Perkin-Elmer	4 Real Time	256 Kb	256 Kb	3	80 Mb
	1 Batch	768 Kb			
SEL	2	192 Kb	64 Kb	1	40 Mb

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ADVANCED FIGHTER AVIONICS SIMULATION DESIGN: THE SIMULATE/STIMULATE QUESTION

By

R. BRUCE McCREARY
Air Force Human Resources Laboratory
Operations Training Division
Williams Air Force Base, Arizona

ABSTRACT

In the real-time simulation of advanced fighter avionics systems, a critical design decision is the choice of stimulating the actual aircraft hardware subsystems or simulating the subsystem function via general purpose computer. This case study of a design decision addresses the effects on many aspects of the aircraft training or research device; training features/research capability, reliability and maintainability as well as major impact on the development/delivery schedule.

INTRODUCTION

The Fire Control Computer (FCC) of the F-16 avionics suite is the primary processor and system data bus (multiplexed serial data) controller. The successful and timely integration of an F-16 avionics simulation is therefore keyed to this critical on-board computation/communication system.

Due to the high technical risk of the complex avionics simulation and schedule restraints, three major design approaches were pursued. The first was the utilization of the actual on-board Fire Control Computer system and the stimulation of this device by supplying all external inputs normally received in the aircraft. Another design pursued was the translation of the software program called the Operational Flight Program normally run in the Fire Control Computer from JOVIAL into FORTRAN, which could then be integrated with the flight simulation in the simulator general purpose computer. The third design approach which was followed to successful completion was to simulate the Fire Control Computer's functions based on the operational specifications and derived primarily from the equation derivation level of aircraft system documentation. This design selection represents a major departure from present industry practice. The reduced cost and improved training/research capability as well as significantly reduced implementation schedule indicate that the automatic acceptance of aircraft hardware engineers and manufacturers suggested techniques may be adversely affecting key high-technology design decisions in training/research simulation devices.

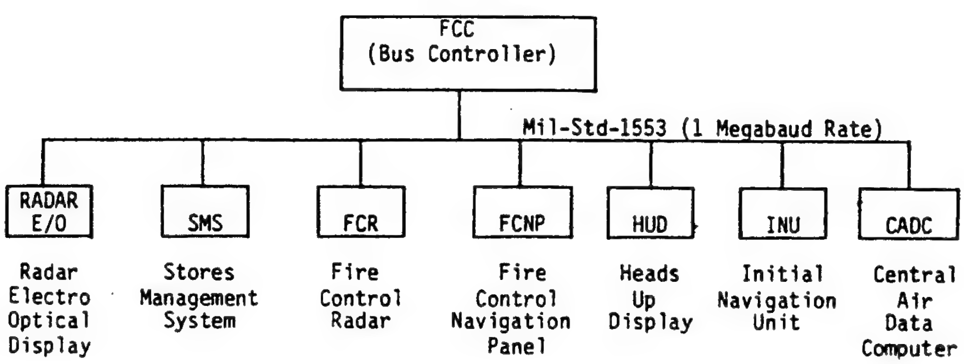
BACKGROUND

F-16 Simulator Program

The Advanced Simulator for Pilot Training (ASPT) F-16 simulation program was designed after the successful A-10 "phased" conversion of an existing T-37 cockpit. The F-16 phase I effort was comprised of minimum objectives directly comparable to those of the A-10 program (1), with a prioritized list of Phase I goals which markedly extended the simulator's capability.

The F-16 Avionics System was a critical high-risk component of the program. The goals for this system simulation consisted of a prioritized list (generated by Tactical Air Command) of training capabilities. This list consisted of specific navigation and air-to-ground (A/G) delivery modes via the Heads Up Display (HUD) as well as physical control panel functions such as the Stores Control Panel and Fire Control Navigation Panel. Priorities were based on projected training schedule and needs.

Research requirements included all of ASPT's conventional advanced training features. These include "Freeze", "Set", Reset", weapons release condition Capture and Recall, "Record", "Playback", and specially configured tactical conditions. Special features for avionics system



Aircraft Avionics Mux-bus Configuration

training were anticipated such as on "Freeze" target identification and target tracking information based on Heads Up Display (HUD) symbology. Other special control features were also anticipated, though not defined.

F-16 Avionics System

Although the primary design decision to be discussed is the Fire Control Computer (FCC) simulate versus stimulate question, some background of the aircraft avionics system is helpful for a basic understanding of the problem.

The F-16 avionics system consists of nine primary subsystems with a common high speed multiplexed serial data bus for digital communication. The Fire Control Computer (FCC) serves as the controller for all digital communications between subsystems and is also the primary controller and processor for most of the advanced avionics features available on the F-16. All air-to-ground and air-to-air ordinace delivery modes, except manual bombing and snapshoot gunnery mode, are implemented in the FCC. Heads Up Display (HUD) navigation is also supported by the FCC.

The Fire Control Computer (FCC) is a moderately high speed 16-bit digital mini-computer built by Delco. The Delco "Magic 362-F" (FCC) has 32K bytes of random access core memory and has floating point arithmetic instructions. The FCC interfaces with the rest of the avionics system primarily through its Mil-Std-1553 serial data interface, although it also has analog and discrete channels.

AVIONICS SYSTEM DESIGN ALTERNATIVES

Stimulate the Aircraft Hardware

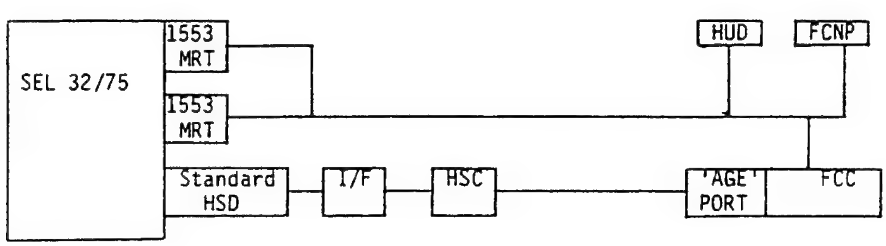
This approach strikes a warm spot in the hearts of pilots and aircraft hardware manufacturers alike. The key potential advantage with stimulating the F-16 FCC is that the onboard operational flight program (OFP) might be used without modification. This should result in excellent simulation fidelity as well as the capability to easily update to new software changes in the aircraft (block updates). This approach would also appear to minimize simulator software and hardware since the aircraft FCC will control the avionics system. These potential advantages had a number of implementation shortfalls.

Stimulation Implementation

The conventional "stimulate" approach was considered the lowest risk approach and was therefore a primary early effort. The hardware configuration to support this approach had already been defined by the Air Force Avionics Lab (AFAL) at Wright Patterson AFB as well as the in-development Singer F-16 simulator. Two key hardware interfaces are required to support this approach. A sophisticated device is required to allow the general purpose (GP) computers complex to act as multiple remote terminals (MRT) on the 1553 mux bus. This MRT device allows the GP computer to respond normally to the FCC as the Inertial Navigation Unit, Central Air Data Computer, Radar, or any other aircraft subsystems that are not present. For example, the Stores Management Subsystem was not available within the program schedule. The complexity of the MRT interface is due to the 1553 communications protocol, primarily the requirement for a subsystem to respond with valid status within five micro-seconds after a command transfer to that sub-system. Since GP computer software intervention is not possible within that time frame, high speed processing and memory is required within the interface. (There are also other stringent protocol requirements.) The MRT device may also serve as a bus "monitor" to capture key intra-subsystem data, or as the bus controller. This interface did not exist for the ASPT SEL 32/75 GP computers. The contract for this interface was let in the first months of the program. The final product was delivered about two years later, more than a year behind firm schedule commitment despite technical relaxation of specifications. This development had been considered medium risk, since the subcontractor had developed a similar device with less sophistication for several other computers.

The other primary interface required to support the FCC in a simulator system is an interface to the FCC's Automated Ground Equipment (AGE) port. This interface allows GP computer control such as halt and run, program loading, and rather slow speed indirect memory access to the FCC through a special set of FCC registers. The interface is an adaption of the High Speed Controller (HSC) interface of the production ground support mini-computer system. This interface was constructed and tested via contract within schedule. Outstanding support was provided by AFAL, which had previously constructed the device for another computer.

The hardware "stimulation" approach got more involved when the advanced training/research features had to be considered, since the FCC's software (OFP) was not designed for simulation. Scoring of weapons delivery, for example, is rather challenging. One method is to access the FCC memory locations for computed impact coordinates through the AGE port after detecting a weapon release command on the 1553 mux bus to



"Stimulation" Hardware System Diagram

the Stores Management System. A less involved method is to run a ballistics model in the GP Computer to score in parallel at weapon release time, again detected by bus data to SMS. The implementation of a "Freeze" function is also more than a trivial solution. One method is to utilize the bus monitor to store the command and data stream from the FCC. At "Freeze" time, the FCC is halted, the BCU interface is switched to bus controller mode, and the last list of stored data transfers is run continuously. An alternate method involves freezing the position and attitude data from the INU and accessing a few key integrating variables in the FCC through the AGE port. These problems were not solved on site as this approach was delayed more than a year and a half by subcontracted MRT interface schedule slipages. Microcode problems in supporting the complex multiple remote terminal capability in real time were a primary problem. The stimulation approach was finally dropped to provide the full support to the successful third approach as on-line capability was demonstrated.

Emulate the FCC (Translation)

This approach was based on the translation of the FCC software OFP from its source language, JOVIAL, into FORTRAN. The FORTRAN equivalent could then be compiled and executed in the basic flight simulator SEL 32/75 GP Computers. This high level language translation was required because a JOVIAL compiler was not available for the SEL 32 computer. The hardware configuration to support this approach is the same as that of the simulation approach; considerably simpler than the stimulation effort and offering direct control over the avionics system.

Translation Implementation

The major effort in this approach was the massive translation effort as well as the integration of this "foreign" software into the simulator system. This approach was supported through a partial translation effort. The effort was dropped due to the projected complexity of debugging and integrating the massive translated program. The complexity was due to the architecture of General Dynamics Operational Flight Program (OFP) which was constrained by severe memory and execution time limitations. The integration problem was again related to this OFP's "real-world" derivations versus the more real time efficient simulation models. Insufficient manpower, calendar time, and computer systems time for the translation, integration, and debug of this approach led to this approach's demise early in the program. The effort was greatly reduced, then dropped to provide full support to the simulation design approach as it demonstrated on-line capability. This approach should not be seriously considered unless the host GP Computer has a JOVIAL compiler or schedule and software manpower are not considerations.

Simulate the FCC

The objective of the FCC simulation approach was to minimize hardware and software complexity and allow early on-line operation with a prioritized growth of the simulation envelope. The complexity of the hardware configuration to support this approach is drastically reduced by assuming the FCC's role of 1553 bus controller. The configuration will be defined in the implementation section.

This design approach was to accurately model all FCC outputs to the hardware-pilot interface subsystems implemented in Phase I of the ASPT F-16 emulation, i.e., Heads Up Display and Fire Control Navigation Panel (FCNP). FCC internal computations and communications are eliminated wherever possible. This eliminates the requirement for an Inertial Navigation Unit (INU) math model and reduces the complexity of the Fire Control Radar (FCR) subsystem model.

No malfunctions or degraded modes are simulated except for total subsystem failures; i.e., FCC, CADC, INU fail. The FCC simulation approach is of course ideally suited to support the various avionics failure modes when research or training requirements for this enhancement are generated.

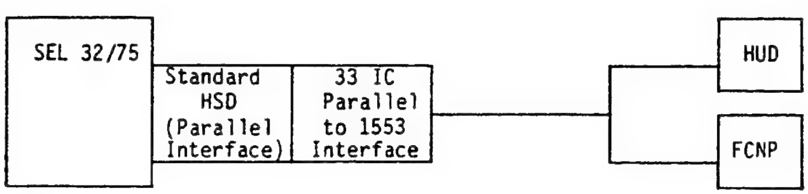
The functional simulation of the FCC, therefore, shall extend only to the man-machine interface. No attempt to model the internal architecture of the operational flight program (actual FCC software) was made due to the following reasons:

- Weapon delivery modes and navigation modes are not independent structural entities due to memory limitations. This is not consistent with the requirement for prioritized growth of capability which can be pursued as parallel development effort.
- OFP is generally not designed to integrate efficiently with the simulation flight model.
- OFP uses re-entrant routines extensively.
- OFP is cluttered with failure testing and degraded modes.

Simulation Implementation

Hardware

The GP computer interface problems were vastly reduced by assuming the FCC's role as bus controller. The MRT device sophistication was not required, and a simple parallel to serial 1553 interface (33 integrated circuits) was



Simulation Hardware system Diagram
(Same for Translation)

designed and built in-house. This device was mounted on a connector board to an off the shelf parallel interface (High Speed Data set - HSD) for the SEL 33/75 computer. All bus communications are under direct software control by the simulator GP computers. The AGE port interface was no longer required, since the FCC is not used.

The aircraft hardware subsystems used in the simulator (HUD, FCNP) receive all digital, discrete, and analog signals normally presented for any of the simulated operating modes at data rates greater than or equal to that supported by the aircraft. Communications with other simulated subsystems such as the SMS or FCR take place through memory shared within the same host computer. The SMS subsystem had to be simulated because a critical component of that system, the Central Interface Unit (CIU) was not available within schedule. The display of the SMS subsystem, the Stores Control Panel (SCP) was interfaced and supported by the SEL 32/75 GP computer system. The interface and extensive interactive software development was a considerable effort and offered no advantages over the use of the aircraft hardware.

Serial Data Transmission Rates (Hertz)

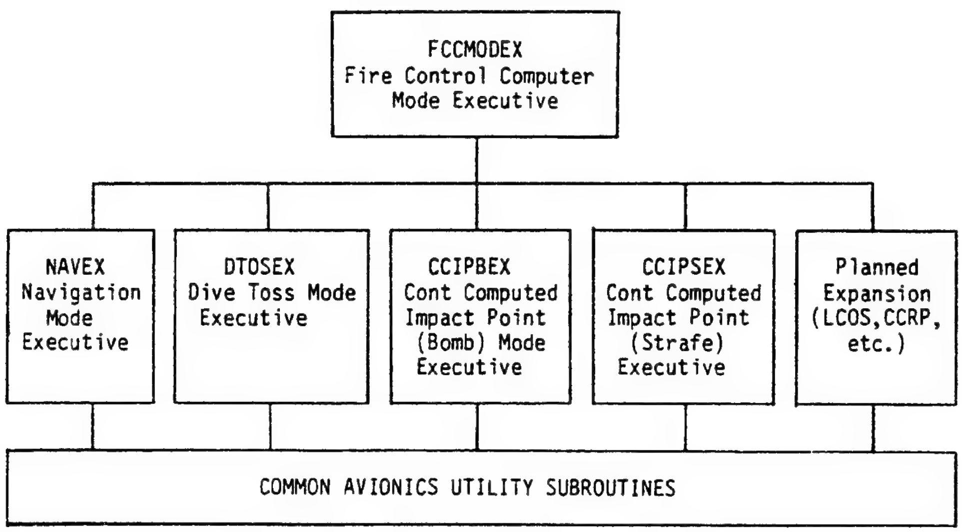
Aircraft	Simulation
50	60
25	30
12.5 or less	15

Mode, VIP Mode, Snapshoot Mode and LCOS Mode have been added proving the ease of expansion into the air-to-air simulation capability.

The design concept of allowing prioritized growth capability while maintaining a "clean" well structured system was especially critical due to the extremely compressed schedule. The development time for each new avionics A/G delivery mode proved to be greatly decreased, as each mode uses the same avionics utilities subroutines.

In the area of research support, the avionics simulation approach was invaluable in its ease of interface with the ASPT's preprogramming research system since all "FCC internal" variables as well as HUD information were directly accessible in the other simulator general purpose computers. Target tracking and weapons scoring, for example, were directly available to the Student Data System (SDS) and graphics displays at the Advanced Instructor/ Operator Station through shared memory.

This approach was followed to successful accomplishment of all design goals for Phase I within the 300 day schedule. More than fifty F-16 pilots have been trained (with research data collected) in all the visual air-to-ground modes as well as enroute navigation, ILS, takeoff and landing. Air-to-air capability is being added in parallel with visual system updates to accommodate research requirements in this area. Excellent fidelity and training/ research capabilities have been demonstrated.



Simulation Modular Software Architecture

Software

The desired software architecture was one which could easily support the independent development of specific A/G and navigation modes, thus enabling a smooth, prioritized growth of capability to match research and training requirements. A "top down" structural approach within each mode was applied to take advantage of the similarities between modes; each mode having an executive program which basically consists of an organized series of common utility subroutine calls. Note: Manual

CONCLUSION

All three approaches were technically sound despite the various difficulties associated with each. Each approach has merit for a particular simulation requirement.

The hardware "stimulation" of the FCC, for example, is ideally suited to a system which is intended for the validation and verification of on-board aircraft avionics subsystems. In a training environment, however, there are design penalties to be considered as a result of the loss of direct avionics system control. System

hardware complexity has a major impact on acquisition and life cycle costs as well as reliability/maintainability. The difficulties in supporting conventional training features has a major impact on software and hardware complexity. Even minor updates to the OFP which represent little or no operational change require analysis and will most likely cause software changes due to the relocation of key variables (used for tracking, scoring and initializations) within the FCC's memory. (Singer Co. has spent considerable effort in developing software to support this difficult task for the F-16 production simulator).

In a training research or operational research environment, this approach is extremely cumbersome. The software effort and expertise required for capturing and processing large amounts of FCC internal information or implementing minor modifications in operational characteristics (i.e., mode or Hud symbology, switchology or control function changes) is phenominal. Post-mortum research answers are the result of this type of "hands-tied" engineering situation where the aircraft component (FCC) is in control rather than the simulator GP computers.

The software "emulation" of the FCC has merit in operational research and training/research only if the host GP computer has a JOVIAL compiler. (The source high-level language of the FCC's software OFP). The "emulation" approach could then possibly compete with the hardware "stimulation" approach for OFP software validation if lack of hardware facilities and cost were primary factors. The positive attribute of this approach for simulator applications is that the software architecture and basic integrity of the OFP is maintained. In the "ideal" world of simulation, however, many of the algorithms may be unnecessarily complex and real-time consuming. The integration of this "foreign" software with flight dynamics and advanced training software is also a major software task. Detailed knowledge of the OFP and FCC hardware configuration is needed for an efficient implementation.

The "simulation" system approach to the FCC/avionics simulation affords the most direct control, minimum hardware complexity, and greatest ease of integration with the flight dynamics and advanced training software. Because of these positive features, the "simulation" approach is most appropriately applied to a training/research or operations research simulation effort. In these environments, the penalty of extended software development is more than offset; particularly when priorities can be placed on specific avionics system simulation capabilities and training or research may procede while software development continues on lower priority modes or capabilities. With this approach, critical training or research problems may be defined and solved 1-2 years earlier, minimizing early program aircraft and pilot losses. Ultimate fidelity is not sacrificed and system reliability and maintainability are enhanced.

In closing, the primary point to be made regarding a "stimulate" versus "simulate" design decision is that a good selection is based on the specific projected requirements, cost and schedule for the simulation. Information and recommendations from aircraft hardware manufacturers or facilities whose requirements are the evaluation of aircraft hardware are extremely valuable. The program manager or design engineer must remember, however, that most of these resources have little understanding of the simulation training/research environment and may be fixated on the complexity of real-world aircraft system problems. If validation of aircraft subsystems is not a requirement, a simulation of that subsystem may be more appropriate; particularly when that subsystem serves as a primary processor and communications controller for the entire avionics system, as in the case of the F-16 Fire Control Computer.

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1. Cyrus, M. and Fogarty, L., Advanced Simulation for New Aircraft. Proceedings of the Eleventh NTEC/Industry Conference, November, 1978.

ABOUT THE AUTHOR

Mr. R. Bruce McCreary is project engineer for the F-16 Avionics simulation program at the Air Force Human Resources Laboratory. He is presently involved with micro-processor application to real-time interface, peripherals, and computational areas of simulation. His staff responsibilities include engineering analysis and support of alternate visual system technology development.

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THE APPLICATION OF A SIX-DEGREE-OF-FREEDOM PILOTED SIMULATION IN SUPPORT OF THE F-14 FLIGHT RESEARCH PROGRAM

Harriet J. Smith and Einar Enevoldson
NASA Ames Research Center
Dryden Flight Research Facility
Edwards, California

Abstract

Simulation played a key role in the Navy/NASA F-14 flight research program. A piloted six-degree-of-freedom nonlinear simulation was integrated into the flight program to aid in flight planning and to prepare the pilot for the high-risk maneuvers encountered in the program. The development of the F-14 simulator and the manner in which it was integrated into the flight program are described.

Introduction

The F-14 exhibits a number of the undesirable characteristics associated with high-angle-of-attack flight, such as wing rock, roll reversal, and departures. Significant effort has been devoted to finding solutions without compromising the aircraft's performance. NASA became involved with this effort early with the development of the aileron-rudder interconnect (ARI) for the unslatted aircraft, and more recently in developing an ARI suitable for the current F-14 configuration. This work was initiated by the NASA Langley Research Center, and utilized the Differential Maneuvering Simulator (DMS). In 1979, NASA began full-scale flight tests to evaluate and make appropriate modifications to the ARI thus developed. Simulation was used extensively throughout the flight test program for flight planning and pilot familiarization, and also as an analysis tool. References 1 and 2 present some of the highlights of this program. The manner in which simulation has been used as an analysis tool is explained in Reference 3. This paper focuses on the role that the Dryden Flight Research Facility's six-degree-of-freedom piloted simulation played in supporting the flight tests.

Nomenclature

b	span, m
C_{ℓ_p}	nondimensional rotary stability derivative, $\dfrac{\partial C_\ell}{\partial \frac{pb}{2V}}$
C_{ℓ_r}	nondimensional rotary stability derivative, $\dfrac{\partial C_\ell}{\partial \frac{rb}{2V}}$
C_{ℓ_β}	effective dihedral parameter, $\dfrac{\partial C_\ell}{\partial \beta}$, deg^{-1}
C_{n_p}	nondimensional rotary stability derivative, $\dfrac{\partial C_n}{\partial \frac{pb}{2V}}$
C_{n_r}	nondimensional rotary stability derivative, $\dfrac{\partial C_n}{\partial \frac{rb}{2V}}$
cg	center of gravity
g	gravitational constant, 9.81 m/sec^2
M	Mach number
p, r	angular velocities about the x and z body axes, deg/sec
SAS	stability augmentation system
V	true airspeed, m/sec
α	angle of attack, deg
β	angle of sideslip, deg
δ_a	differential tail deflection, deg
δ_r	rudder deflection, deg
δ_y	lateral stick position, cm

F-14 ARI Development

Several factors were responsible for the lack of success with the early attempts to develop a control system modification which would improve the high-angle-of-attack characteristics of the F-14. The lack of full-scale flight data during the development phase was one such factor. Therefore, the most recent effort utilized an integrated approach involving real-time pilot-in-the-loop simulation, flight testing, and engineering analysis to develop an ARI. This control system modification was designed to enhance the departure resistance of the F-14 and to improve the flying qualities of the aircraft by eliminating roll reversal and alleviating wing rock at the high angles of attack.

A specially configured F-14 was loaned to NASA for these tests. The aircraft selected was F-14 1X (Fig. 1). Several safety features were incorporated in the test aircraft. These include a spin recovery system consisting of a 26-foot spin chute, canards, and a battery-operated auxiliary power unit; a frangible front canopy; and an engine stall warning system. In addition, the automatic flight control system (AFCS) computers were modified to include a variable-gain calibrator (VGC), which permitted nine control system variables to be varied (five discrete values were available for each variable) in flight.

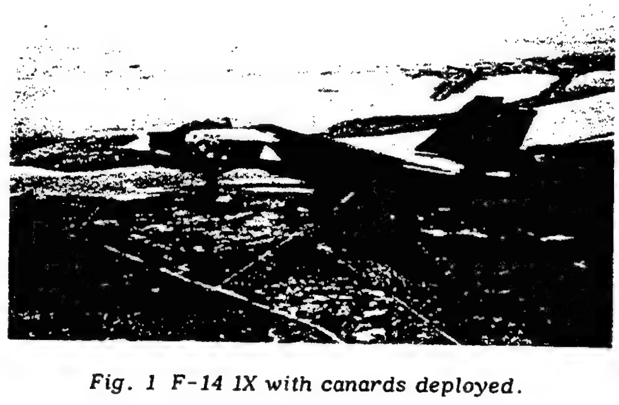
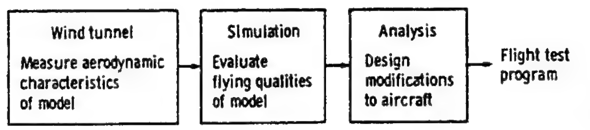
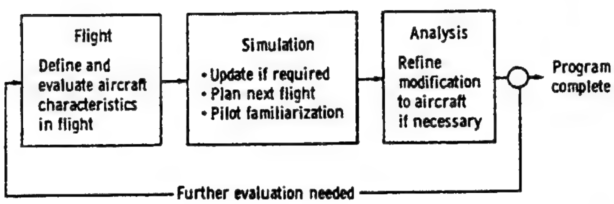


Fig. 1 F-14 1X with canards deployed.

Simulation has played a key role in this program from the initial ARI concept to the final analysis of the modified system. Figure 2 illustrates conceptually the manner in which simulation was integrated into the program. The preliminary phase of the program, conducted at the NASA Langley Research Center, utilized the DMS to aid in the initial design of the ARI and to conduct a preliminary evaluation of the system. The system was then installed on F-14 1X and subsequently flight tested at the Dryden Flight Research Facility, where the control system was further refined and evaluated. During the flight tests, the Dryden simulator was used for flight planning and pilot familiarization, and also as an analysis tool. As this figure indicates, this was a continuing process with adjustments being made to both the control system and the simulator throughout the flight program.



(a) Preliminary phase of program.



(b) Flight test program.

Fig. 2 Diagram of the process of integrating flight testing, simulation, and analysis.

Hardware Development

At Dryden a small staff (seven people) design, build, program, and maintain simulators for approximately a dozen different aircraft at any one time. Therefore, care is taken to avoid unnecessary complications or features without compromising any required capabilities. The physical characteristics of a simulator can vary significantly from a rudimentary engineering simulator to an iron bird utilizing an actual aircraft. Likewise, significant differences exist in the cues provided (e.g., motion, visual). Considerable effort has gone into trade-off studies to determine the level of complexity or realism which is necessary. No single answer can be given to this question; the objectives and nature of the program determine the simulation requirements. In recent years, simulation has assumed an increasingly important role in systems development; however, the primary justification for simulation at Dryden historically has been the need for flight planning and pilot training. Pilot training is intended to include developing and practicing emergency procedures in the event of various system failures or deviations from predicted aerodynamic characteristics. The objectives of the F-14 program included definition of the limits of controllability of the ARI-equipped airplane, identification of critical flight conditions, and the development of techniques for recovery from high yaw rates. These were factors which influenced the design of the F-14 simulator.

Because of the need to practice emergency procedures, it was necessary to include in the simulator cockpit the critical elements of the airplane cockpit. The pilot played a key role in defining these requirements. In addition to photographs and drawings of the cockpit, an actual aircraft was also used to identify the necessary hardware and to verify key measurements so that the important distances and angles were duplicated. The pilot identified all those instruments, buttons, switches, etc., which he considered critical or highly desirable. In some cases, such as the stick grip and throttle, actual flight hardware was used. In other cases copies were made. In all cases care was taken to ensure that the location of the instruments and controls were in the proper location, the instruments looked sufficiently similar to the actual aircraft instruments, and the control feel and throws were correct. Control feel was provided by a general purpose programmable electric stick which was developed in-house.[4] A photograph of the simulator cockpit is shown in Figure 3.

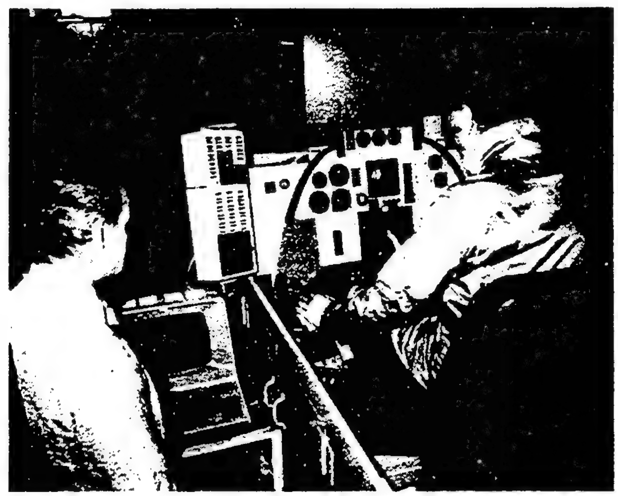


Fig. 3 F-14 simulator.

When designing a simulator cockpit to be used for practicing high-risk maneuvers and emergency procedures, physical characteristics can become extremely important, and the designer must be wary of innocuous-looking compromises in hardware. Spin recovery in F-14 1X requires moving the weapon-select switch on the stick grip. In simulation this was easily done with the right thumb. Because of a combination of factors, including the use of gloves, a slight difference in seat geometry, and a slight restraint harness interference, it was found difficult to operate that switch in flight as planned. Fortunately, the problem was discovered during early build-up maneuvers and not in an emergency situation. In this particular case, it was not necessary to make a hardware change because it was found the switch could be operated in flight with the left thumb. This incident does point out the potential danger of practicing something on the simulator that cannot be transferred to flight.

Not all design features were dictated by safety concerns. Dryden's F-14 simulator incorporates a number of user convenience features which make it especially well suited to support a flight research program such as the F-14 program. For example, a mode control panel has been included which is just outside the cockpit but easily accessible to the pilot. This panel provides a simple, convenient means of controlling the simulator. This includes, for example, resetting

the initial conditions by increasing or decreasing desired parameters or capturing the flight conditions at any time during a maneuver to use as the initial conditions for a series of comparison runs. In addition, control system configuration, real-time display parameters (e.g., CRT and brush recorders), engine(s) status, and system failures can be easily controlled by the pilot or project engineer/flight planner. Normally the project engineer operates these controls and works closely with the pilot and flight controller. This team approach and the readily accessible and versatile control panel contribute to a highly productive operation. Moreover, there is direct face-to-face contact as well as continuous and easy conversation between the pilot, project engineer, and flight controller during a simulation session. The likelihood of errors in communication are greatly reduced when the team members can see what is happening. In addition, this mode of operation allows for much greater familiarity with the maneuvers and a better appreciation for potential problems.

Software Development

Simulation credibility is directly related to the fidelity of the aerodynamic model, and NASA has put significant effort into ensuring that the simulator provided the required fidelity. The initial simulation at Langley was developed from wind-tunnel derivatives which were later adjusted to reflect the subjective opinions of a number of pilots who had flown the F-14. During the flight test program which followed, the first step taken to update the simulator was the development of the high-angle-of-attack data base. The rotary stability derivatives (C_{ℓ_p}, C_{ℓ_r}, C_{n_p}, and C_{n_r}) included contributions from two different types of wind-tunnel testing techniques: forced oscillations tests and rotary balance tests. This was accomplished by separating the oscillatory and the rotational components of the total angular velocity prior to each integration step. Before the numerical integration was resumed, the total damping (consisting of the oscillatory and rotary components) was evaluated. This scheme worked remarkably well and reproduced, at least qualitatively, the characteristics of the limited amount of full-scale F-14 spin data. In addition, a significant portion of the early tests was for the purpose of validating and updating the simulator. Eleven flights were devoted to the lateral-directional and longitudinal maneuvers required for obtaining the necessary data for parameter identification. These data were analyzed using a modified maximum likelihood estimation (MMLE) technique to determine the derivatives, and the aerodynamic model was appropriately updated to reflect these changes. This was not the final model however; as Figure 2 indicates, updating the simulator was a continuing process that took place throughout the flight program as the flight envelope was expanded. This was done by comparing flight and simulator time histories after each flight and making adjustments to the derivatives as required to obtain satisfactory matches.

Some derivatives changed significantly as a result of this process. Some of the more significant examples are the derivatives C_{ℓ_β}, C_{ℓ_p}, and C_{n_p}. Comparisons of the current values to the initial wind-tunnel data are shown in Figures 4 to 6.[2] The significance of these changes is illustrated in Figure 7 by comparing simulator time histories obtained from the two sets of data.

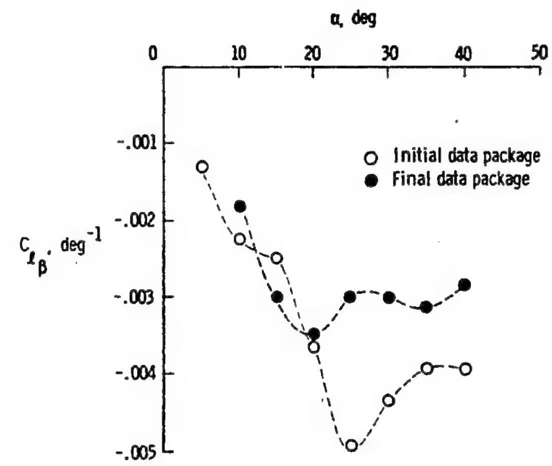


Fig. 4 Initial and current values of C_{ℓ_β} used in the simulation.

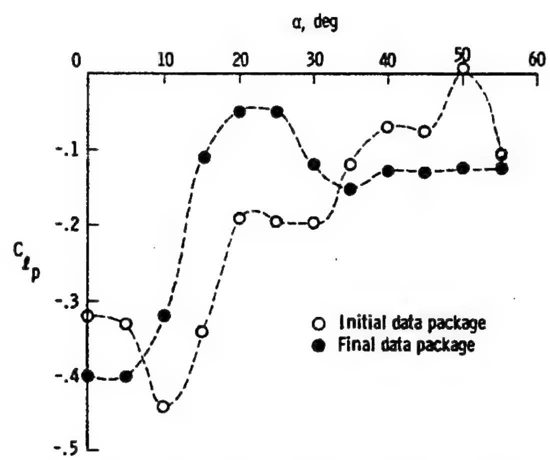


Fig. 5 Initial and current values of C_{ℓ_p} used in the simulation.

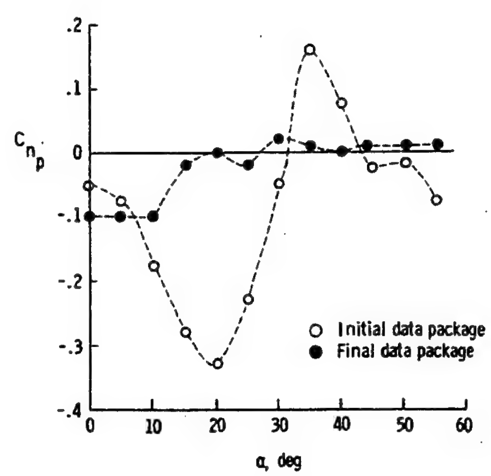


Fig. 6 Initial and current values of C_{n_p} used in the simulation.

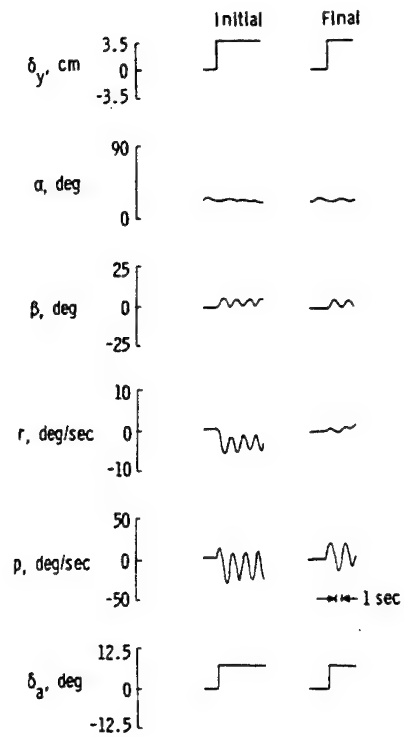


Fig. 7 Comparison of the response of the simulator with the initial and final set of aerodynamic data (all SAS off, M = .51, altitude = 9,190 m).

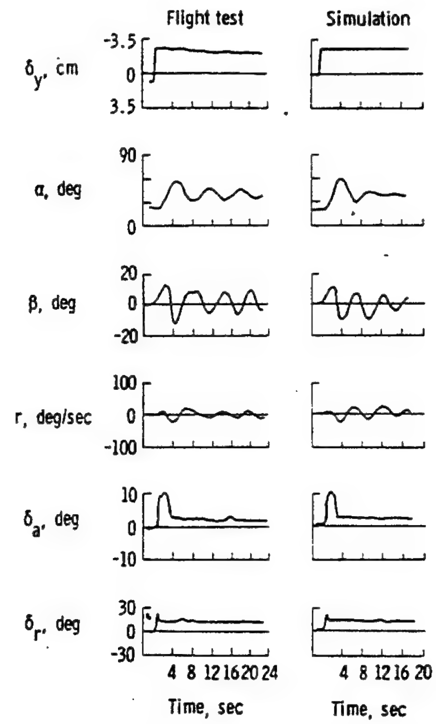


Fig. 8 Airplane and simulator responses to full cross-controls and full aft stick applied from 1-g trimmed flight at α = 25° (aft cg position).

Not all discrepancies between flight and simulation can be attributed to inaccurate wind-tunnel data. Insufficient data can often lead to invalid interpolations and extrapolations. Just as innocuous compromises in the hardware can prove to be significant, the same can be said for the aerodynamic model. Late in the program, during an evaluation of wing rock suppression an uncommanded yaw divergence occurred that was not predicted on the simulator. Analysis later revealed that too large a grid had been used to determine C_ℓ versus β, and a small but very significant flat spot was missed. After the appropriate change was made, the simulator accurately predicted the yaw divergence.

Although the aerodynamic model will undoubtedly undergo other subtle changes as the F-14 flight program continues, the current model implemented on the simulator results in reasonably high fidelity simulation. An example of this is shown in Figure 8. The flight and simulator responses to identical control inputs are compared. This was a large amplitude maneuver resulting from a full cross-control and full aft stick applied from a 1-g trimmed flight at α = 25°. As can be seen, the simulation results substantially agree with the flight data.

Pilot Training

Simulation has become an integral part of nearly every flight program conducted at Dryden. For high-risk programs such as the F-14 high-angle-of-attack program, a piloted simulation has been established as an absolute requirement. The primary motivation for pilot training in a program such as this is naturally safety. As discussed in "Hardware Development" and "Software Development," appropriate physical characteristics of this training tool and a valid aerodynamic model are essential. Equally important is the ability to use this tool.

For maximum effectiveness of simulation as a training tool, it is necessary to have a highly motivated, imaginative pilot willing to spend many hours working on the simulator for every hour of flight. In the F-14 program, the pilot, flight test engineer, and flight controller formed a team which worked closely together developing and practicing emergency scenarios. Various system failures were introduced into the simulator at different times to investigate the possible reactions to these failures and determine when the recovery devices (e.g., chute, canards) should be deployed or when it became necessary to eject. In addition, these emergency procedures were practiced with the controller giving the appropriate calls throughout the mission. An added measure of safety was provided in this program by the use of the backup pilot as the flight controller.

Critical displays were identical in the simulation laboratory to those in the flight control room. This permitted the engineers who would be monitoring the flights to become familiar with the tests during the simulator practice sessions so that they too would be prepared for potential emergencies. No maneuvers were performed in flight that had not been practiced first on the simulator, both under normal conditions and with simulated system failures. Simulator results were recorded on strip charts in the same format as the real-time flight data. These strip charts were often brought to the control room during the ensuing flight so that quick comparison could be made to assure flight test engineers that the flight results were following the simulator predictions. Few surprises were encountered during this program.

Every attempt was made to ensure the largest possible margin of safety during these tests. In addition to simulating system failures, the aerodynamic model was also varied to investigate the effects of deviations from predicted aerodynamic characteristics. The basic simulation, with the parametric variations used, encompassed essentially all the behaviors encountered in flight. The training that resulted from investigating all these cases gave the pilot a broad understanding of the airplane's probable response under a very large variety of conditions. Numerous preconceived responses to aircraft gyrations were available that would have been inappropriate and uncomfortable, and would no doubt have been used in the absence of simulation. Maneuvers that would have resulted in alarming excursions or emergency recoveries had they been experienced for the first time in flight were routinely handled without incident.

Because one of the objectives of this program was to establish the limits of controllability of the ARI-equipped airplane, it was necessary to establish yaw rate recovery boundaries for these tests and develop techniques for recovering from high yaw rate conditions Initially a yaw rate boundary of 40 deg/sec was used. The simulator was used in conjunction with the flight tests to systematically push out this boundary until a boundary could be established that would permit the test objective to be met. To extend this boundary, a comprehensive set of predictions was made using the simulator. The simulator was flown to the desired yaw rate condition, capturing the initial condition (IC), then successively applying each of several recovery techniques from that IC. The process was repeated at 5 deg/sec yaw rate increments, and yaw deceleration was measured and plotted for each recovery technique (Fig. 9).

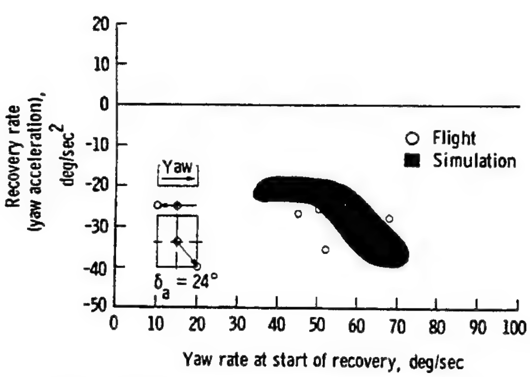


Fig. 9 Effectiveness of recovery controls.

Qualitatively, the effects of controls on sideslip and bank angle were used to supplement the yaw acceleration measurements. Flight tests were then made which followed the pattern of the simulator tests, but in which the rate of boundary extension, the step size, was determined by the degree of correlation with predictions and by the predicted margin of control available. Recoveries which were either not promising or did not add confidence to the correlation were not attempted in flight. Although the simulator predicted recovery from even larger rates, no yaw rates greater that 80 deg/sec were experienced in flight. The largest yaw rate experienced with the ARI-equipped airplane was 53 deg/sec, which was well within recoverable limits.

Although safety is certainly the primary motivation for pilot training, the quality of the data can be a very important secondary reason for using simulation to train the pilot. This can be very important in a program where precise conditions must be achieved to obtain the desirable data. In this program it was learned that the timing and sequencing of the control inputs were sometimes critical in achieving the maximum response. Not only would it have been necessary to repeat the maneuvers many times, in some cases the potential aircraft response to some of the aggravated control inputs might never have been experienced.

Flight Planning

The second major application of simulation at Dryden is in flight planning. Although flight planning per se does not necessarily require active participation by the pilot, in practice, flight planning and pilot training are often one operation. Particularly in a program such as the F-14 program where an objective of the program was to define potentially hazardous maneuvers and conditions, the pilot training often became an indistinguishable part of the flight planning. Moreover, a concern for safety was a major reason for flight planning as well as pilot training in this program. However, a strong motivation for using simulation as a flight planning tool in this program, just as in any other, was the potential savings in cost that could be realized. To explore every potential hazardous maneuver and flight condition in flight would require a prohibitively large test matrix. This is particularly true when considering the high risk associated with these tests and the consequent slow build-up process that would be required.

By using a simulator, two factors aid in reducing the test matrix. First, by investigating the maneuver on the simulator before flying, it was found that many maneuvers could be eliminated because they were uneventful. Secondly, as confidence was gained in the simulator and test procedures, larger steps could be taken and the build-up process could be significantly speeded up. Without simulation, there is a tendancy to thin the matrix on the basis of early results and impressions. In the F-14 program, early results at low Mach numbers indicated more severe departures for controls applied from a steady angle of attack. It would have been erroneous to assume this was generally true. At high Mach numbers the most severe maneuvers occurred when controls were applied during abruptly increasing angles of attack. This behavior was predicted by simulation. In general, the behavior of modern fighters at high angles of attack is so unpredictable that no flight test program can fully explore it. Although simulation is no guarantee that important features will not be missed, it does minimize the likelihood of overlooking critical situations.

The F-14 simulator is especially well suited for use as a flight planning tool. Many of the features described in "Hardware Development" significantly enhanced the efficiency of the flight planning operation. The IC capture feature is a good example of this. This allows the pilot to "freeze" the flight condition anywhere in a maneuver and replace the IC table with the flight conditions at that point in the maneuver. This permits the pilot to investigate many alternative pilot actions following a given situation without having to refly the entire maneuver. This feature, plus the convenience of having all the simulator controls readily accessible to the flight planners, results in an extremely effi-

cient operation. In a one-hour session on the simulator, 30 or more maneuvers can be investigated. This compares to 6 to 12 in flight.

As Figure 2 indicates, the flight planning is an integral and continuing part of the flight program. Typically 4 to 6 hours of simulator time are scheduled each week in preparation for flying one flight. Information and experience gained from the previous flight are influential in planning the next flight. Often portions of the previous flight plan are further investigated on the simulator before continuing.

This type of operation requires close proximity of the simulation facility to the users. At Dryden the simulation facility is located in the same building with the pilot and engineering staff; however, during the early phase of this program, the flight tests were conducted at the contractor facility on Long Island and the closest simulator was the Langley DMS. This resulted in minimal use of the simulator. Fortunately, most of these flights were for parameter identification tests, and for these tests this was not a serous handicap. For control system evaluation and refinement, lack of simulation could result in inadequate planning or inordinate delays, which was a consideration in the decision to move the operation to Dryden earlier than originally planned.

Future Plans

During the early part of the F-14 program, considerable attention was given to developing techniques and procedures that would aid the flight controller and flight test engineers in the event of an emergency. Much discussion centered on how many people in the control room should have direct communciation with the pilot and what kind of information was required by those individuals to make timely and appropriate decisions. It was finally decided that engine stall and overtemperature information should be relayed directly to the pilot by the propulsion engineer. To avoid the potential chaos that might occur if several other individuals were attempting to give the pilot emergency information, it was decided that the flight controller would be responsible for all other emergency communication. To aid the controller, a CRT display was developed that consolidated all the emergency information deemed essential in an easy to interpret format. A photograph of this CRT is shown in Figure 10. It presents SAS and engine status, longitudinal acceleration, and recover and eject commands. In addition, it shows the controller where the pilot's controls are and where they should be in the event of a spin. As a backup aid, the controller is provided with a plot of the yaw rate versus angle of attack, which includes the mandatory recovery boundaries. Fortunately, the pilot has never experienced the kind of emergency that could adequately test these procedures. Although every attempt has been made to practice emergencies, up to now it has not been possible to create a realistic emergency scenario in the control room.

The next major step forward in the area of crew training for emergencies will tie the simulation facility into the flight control room. With this capability, which is planned for late 1984, it will be possible to man the control room as if an actual flight were taking place. All the real-time data will be generated by the simulator; however, this will be transparent to the engineers monitoring the flight. The benefits in emergency simulation are obvious. It should become clear if certain information being provided to the controller is

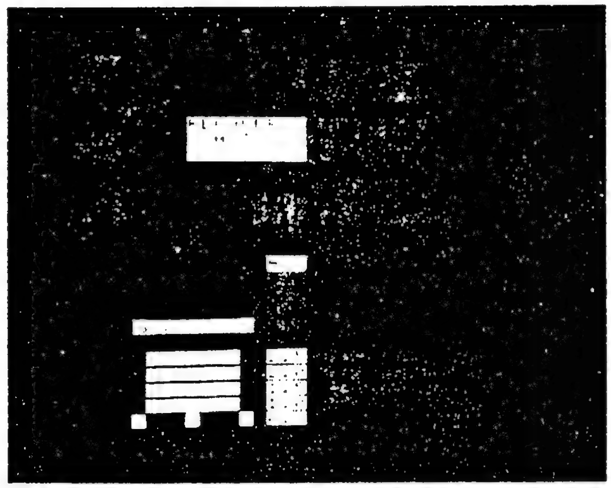


Fig. 10 Computer-driven CRT display used in control room.

redundant or otherwise unnecessary or confusing, or whether critical information is missing. In addition this capability will make the simulator a valuable tool for control room checkout. Complete functional checkout of the real-time software will be possible. Because virtually every program at Dryden is different from previous programs, it is almost a certainty that the first flight will reveal control room anomalies, and as a result, it is often found that the only value from the first flight is to check out the control room. With the ever increasing cost of flight test, this additional simulation capability will soon pay for itself.

Concluding Remarks

This paper describes the role that the Dryden six-degree-of-freedom simulator played in supporting the F-14 flight research program. Dryden's F-14 simulator was designed for the user with substantial input from the pilot. The simulator cockpit was specifically designed to duplicate the important physical characteristics of the F-14 1X cockpit and incorporated many features which aided the pilot and flight test engineer in planning and training for the flights. All maneuvers were planned on the simulator and practiced before actual flight.

The aerodynamic model used in the F-14 simulator was initially developed from wind-tunnel data and was continually updated as flight data were obtained. The high-angle-of-attack simulation was developed by merging data from rotary balance tests with forced oscillation data.

A significant aspect of the role of simulation in the F-14 program was the manner in which it was integrated into the flight program. For maximum effectiveness in a flight research program, simulation cannot be regarded as a separate and distinct phase of the program. The proximity and accessibility of the simulator to the user become important factors in the operation. The simulator used to support the F-14 flight tests was conveniently located in the same building with the users and could be operated by the pilot or project engineer.

In the future it is planned to tie the simulator into the control room which will permit simulated emergencies to be monitored in the control room. This will

significantly enhance confidence in the control room procedures as well as permit complete functional check-out of the real-time software without the necessity of flight.

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THE ROLE OF IN-FLIGHT SIMULATION IN AIRCRAFT TEST AND EVALUATION

Louis H. Knotts and Rogers E. Smith

ARVIN/CALSPAN ATC
Flight Research Department
Buffalo, New York 14225

Abstract

With the flexibility of advanced full authority electronic flight control systems the capability to create aircraft with excellent flying qualities is a reality. Unfortunately, recent examples of aircraft with sophisticated control systems have displayed serious flaws during their initial flight testing which were not evident during the aircraft development process. Recent experience has shown that the inclusion of in-flight simulation in concert with ground simulation, early in an aircraft's development, can significantly improve the final design. An in-flight simulator has the advantage over its ground-based counterpart of providing high fidelity visual and acceleration inputs to the pilot. In addition, it provides very realistic airborne tasks and pilot stress levels. Routine use of in-flight simulators to study critical flight tasks can be extremely cost effective because of their capability to expose potential control system problems which may go unnoticed during ground simulation.

This paper provides an overview of the purpose, design, and operation of past and present in-flight simulators. The advantages of in-flight simulation as well as its critical role in the aircraft development process, are discussed in depth. Potential problem areas in aircraft flying qualities which necessitate the use of airborne simulation are described. Several examples are provided of adverse flying qualities observed in recent aircraft designs which could very well have been avoided by more widespread utilization of in-flight simulation.

Nomenclature

F_s	Longitudinal Stick Force
K	Transfer Function Gain
s	Laplace Operator
T_2	First Order Lag Time Constant, Seconds
ζ	Damping Ratio
θ	Pitch Attitude
τ_e	Equivalent Time Delay, Seconds
ω	Natural Freouency, Rad/Sec
$[\zeta,\omega]$	$s^2+2\zeta\omega s+\omega^2$

What Is An In-Flight Simulator?

An in-flight simulator is an aircraft whose dynamic responses can be modified as desired to match those of other aircraft. The stability and control characteristics of the aircraft can be altered individually to show the effect that a single parameter has on flying qualities, or altered in unison to simulate a specific aircraft. In addition to representing appropriate aircraft response, many of the existing in-flight simulators, or variable stability aircraft, can adapt the cockpit layout, instrumentation, and control system feel characteristics to mimic those of the aircraft being simulated. Control system feel characteristics are an important ingredient in the overall aircraft system which the pilot operates. For this reason such factors as stick force gradients, stick motion, friction, and breakout forces must be variable to provide accurate airborne simulations. Variability in the layout of an in-flight simulator's evaluation cockpit is somewhat restricted to that of the baseline aircraft; however, some cockpit instruments may be adaptable to mimic the aircraft in question. The Display Evaluation Flight Test (DEFT) system is an example of a programmable head up display (HUD) system installed in a variable stability aircraft. This system was developed for the U.S. Navy by General Electric and Calspan to provide a programmable HUD format for airborne studies. It is currently installed in the USAF/Calspan NT-33 variable stability aircraft (Reference 4).

History Of In-Flight Simulation

The first variable stability aircraft was developed in 1948. At that time the NASA Ames Research Center modified an F6F Hellcat with a servo actuated aileron in order to study dihedral effect. Concurrently, the U.S. Navy sponsored modification of an F4U Corsair by the Cornell Aeronautical Laboratory to study Dutch-roll characteristics. Since that time, over thirty aircraft have been modified for use as in-flight simulators while an even larger number of aircraft have been made variable in some sense for flight control or stability research (Reference 1). Table 1 provides a list of the in-flight simulators currently in use in the United States. Two of these aircraft, the Learjet and B-26 are trainers in the sense that their variable stability systems are used primarily to teach stability and control and study aircraft flying qualities in flight. The Gulfstream in-flight simulators are used specifically to train Shuttle pilots and are referred to as Shuttle Training Aircraft (STA). The XV-14B and the X-22A are VSTOL flying qualities research vehicles. The remaining in-flight simulators are used to evaluate specific aircraft or are used for general flying qualities research. As an example of a recent in-flight evaluation project, the AFTI/F-16 aircraft was simulated by the NT-33A to evaluate the approach and landing flying qualities of the AFTI prior to first flight.

TABLE 1

IN-FLIGHT SIMULATORS IN USE IN U.S. IN 1982

LEAR 24	USAFTPS/USNTPS/Calspan
B-26	Calspan
NT-33A	USAF (Calspan)
NC-131H	USAF (Calspan)
X-22A	US Navy (Calspan)
NAVION	Princeton University (Two Aircraft)
XV-14B	NASA Ames Research Center
GULFSTREAM II	NASA Johnson Space Center (Two Aircraft)
F-8 DFBW	NASA Dryden Research Center

How Does It Work?

The variable response of an in-flight simulator aircraft is controlled typically by a full authority "fly-by-wire" flight control system. The evaluation pilot uses a modified set of cockpit controls to drive the aircraft's control surfaces through the variable stability flight control system. The original set of cockpit controls are connected directly to the aircraft's control surfaces and are used by the safety pilot. The safety pilot therefore always has access to a set of controls which have the characteristics of the baseline aircraft. The safety pilot controls the aircraft during normal operations, sets up the configurations to be tested by the evaluation pilot, and assumes control of the aircraft if an unsafe situation develops. Single seat in-flight simulators, such as the XV-14B and the F-8, require special safety features and have more stringent operational constraints than their dual seat counterparts.

The variable stability system of the existing in-flight simulators typically are designed as either response feedback or model following flight control systems. Either analog or digital computers can be used to implement the variable flight control system.

- A response feedback control system is one which measures various aircraft motion parameters, such as, angular velocities, angle of attack, or sideslip and then commands a proportional control surface motion through variable feedback gains. The simulator's natural response characteristics change to the desired values as the feedback gains are adjusted.

- A model following control system generates the desired dynamics of the simulated aircraft using an on-board computer. The simulator's control surfaces are deflected to force the aircraft to follow the computer generated model dynamics. Any errors which develop between the simulator and model responses are eliminated using high feedback gains. Block diagrams of a typical response feedback and a model following flight control system are shown in Figures 1a and b.

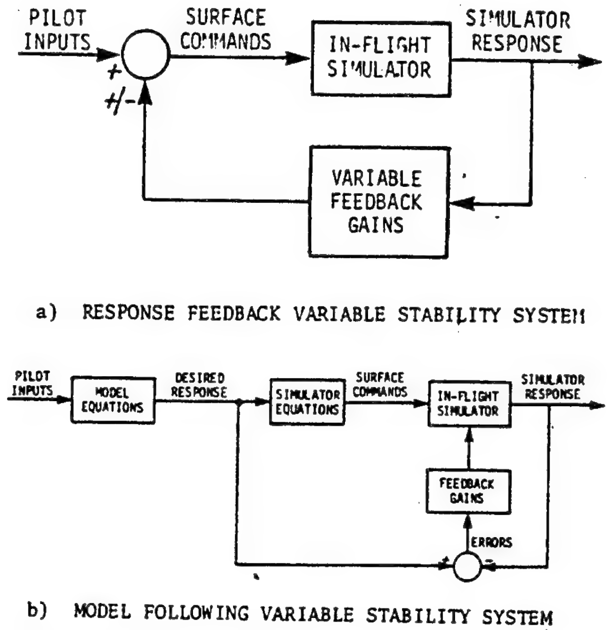

Figure 1: Block Diagrams of Typical Response Feedback and Model Following Variable Stability Flight Control Systems

Why Simulate In Flight?

In-flight simulators, like ground simulators, provide a means to test new aircraft designs in a less expensive and safer environment than the actual test vehicle. In-flight simulators have the added advantage that flight test evaluations are performed while airborne and while performing the actual mission of the experimental aircraft. Both high fidelity moving-base ground simulators and in-flight simulators are undeniably more expensive to operate than less realistic simulators. Compared to the cost of flight testing modern tactical aircraft or implementing modifications to new aircraft designs, the expense of accurate simulation is moderate. Early detection of an undesirable flying quality characteristic of a new aircraft can make the use of accurate simulation studies very cost effective.

As previously mentioned, safety of flight during airborne simulation is typically maintained by a safety pilot who has access to a standard set of aircraft controls. Because the safety pilot can monitor the evaluation of an experimental aircraft design and revert to normal control at any time, potentially dangerous configurations can be safely, yet realistically, evaluated in an in-flight simulator. A further advantage of the safety pilot is that he is able to observe the performance of the evaluation maneuver directly and ensure that the tasks are performed as briefed. His insight can be a valuable source of additional data.

The Roles Of In-Flight and Ground Based Simulation

Both ground based and airborne simulation have essential roles to play in the flying qualities development process. In-flight simulation is not a substitute for ground simulation, any more than

ground simulation is a substitute for flight in the actual aircraft. These evaluation tools should be viewed as complementary rather than competitive. Because of the realism of the flight environment, in-flight simulation should be used periodically during the design process to verify the flying qualities of aircraft for critical tasks. The advantages of in-flight simulation are centered in the following areas:

- Visual Displays
- Cockpit Acceleratons
- Task Realism
- Pilot Stress Levels

The visual displays provided to the evaluation pilot during in-flight simulation are completely accurate because they are due to a real flight environment. Visual displays provided by ground simulators have recently made great strides in realism. Technical advances have made it possible to present images for a variety of tactical missions as well as a day or night landing environment. Although these displays are of great benefit for pilot training, it is questionable whether the visual cues they provide are of sufficient fidelity to explore the unknown flight characteristics of a new aircraft during precision tasks.

Cockpit accelerations of an in-flight simulator are provided by the actual airborne environment and can accurately reproduce a broad range of motions expected of any new aircraft design. A moving base ground simulator provides acceleration cues to the pilot by slowly washing out the steady state motions and attitudes. Typically the cockpit accelerations are not accurately simulated in ground simulations which can lead to misleading flying qualities evaluations.

The realism of aircraft evaluation tasks performed in ground simulators can present further difficulty. In-flight simulation provides the opportunity to carry out actual airborne refueling, formation flying, or air-to-air tracking using real aircraft targets instead of one dimensional images. A precision task of universal interest during the evaluation of new aircraft designs is that of landing the aircraft. The complexity necessary to provide a ground simulator pilot with high fidelity visual, motion, wind, and ground effect cues presents an expensive and difficult problem.

Realistic "stress" levels can be created in an in-flight simulator. Producing a realistic task consists of more than providing an appropriate visual display and cockpit motion. It also requires the pilot to address the task with a level of concentration and aggressiveness which is representative of that needed in the actual airborne environment. This mental attitude is especially critical for precision piloting tasks where corrections must be made quickly and accurately. Airborne simulation provides the capability to perform tasks in flight thus assuring realism in the level of pilot stress during evaluations of a new aircraft or general flying quality studies.

Increased Need For Simulation

Many advances have been made over the past decade in aircraft and control system design. Fly-by-wire aircraft with on-board digital computers and full-authority flight control systems have allowed for reduced static stability aircraft and mission oriented aircraft flying qualities. Unfortunately, experience has shown us that in many instances the application of this high technology has resulted in aircraft with significant flying qualities deficiencies (Reference 10). Rather than simplifying the test and evaluation process, modern control system designs have increased the need for thorough and accurate aircraft simulation throughout an aircraft's development.

Specific reasons which make the use of in-flight simulation essential to the design of modern fighter aircraft are discussed in detail in the following sections.

- High Order Systems

The use of modern control engineering design techniques has contributed somewhat to flying qualities deficiencies. Because the capability exists to build complex flight control systems with many feedback channels and filters, they are often used without simplification. This results in high order motion response of the aircraft and flight control system combination. As an example, a recent fighter design produced an aircraft/flight control system design in which the pitch rate response to pilot input was over 50th order. The fact that this type of high order design often degrades aircraft flying qualities was not appreciated for many years and only became obvious after the most recent generation of fighter aircraft were flight-tested. The addition of complex flight control systems results in aircraft response which does not fall neatly into the flying qualities specifications for aircraft with the five classic modes of response. Typically, in order to evaluate these complex aircraft, design guidelines are used based on an equivalent low order system approximation to the high order system, or the aircraft is simulated on the ground and refined using evaluation pilot comments and rating. Pitfalls are present in both of these solutions. Until the problem areas are resolved, in-flight simulations will continue to have an essential role in refining the design of (aircraft with) complex flight control systems.

- Time Delays

The presence of time delays, created by digital effects and high order design, between control stick inputs and aircraft motion can seriously degrade aircraft flying qualities. Pure time delays can result from the computational time required by digital flight control systems to generate a control surface command. Equivalent time delays are produced from the slow initial response of high order aircraft dynamics. Even the addition of a single first order lag to an aircraft transfer function can significantly increase equivalent time delay. Figure 2 shows a change in effective time delay of over 100 ms as a first order lag filter is added to a sixth order system. An acceptable level of time delay is highly dependent on aircraft type and pilot task-

ing. As a pilot is required to perform more precise tasks, such as air-to-air tracking, less time delays can be tolerated. Figure 3 illustrates the degradation in aircraft flying qualities ratings which result from relatively short time delays in a fighter aircraft during approaches and landings. (References 7, 9). The adverse flying qualities which typically result from time delays are overcontrol of pilot inputs and pilot induced oscillations. Because of the serious problems created by excessive time delays it is critical that aircraft with complex flight control systems be carefully simulated prior to their first flight and in-flight simulation is essential to this task.

HOS Form: $$\frac{\dot{\theta}}{F_s} = \frac{K_\theta (s + .71)}{(s + 1/T_2)[.54,\ 3.9]\ [.6,\ 26][.7,\ 75]}$$

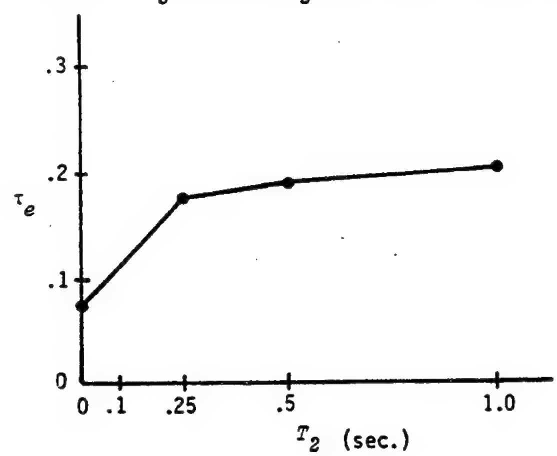

Figure 2: Changes In Effective Time Delay As A First Order Lag Time Constant (T_2) Is Varied (Adopted from Reference 6)

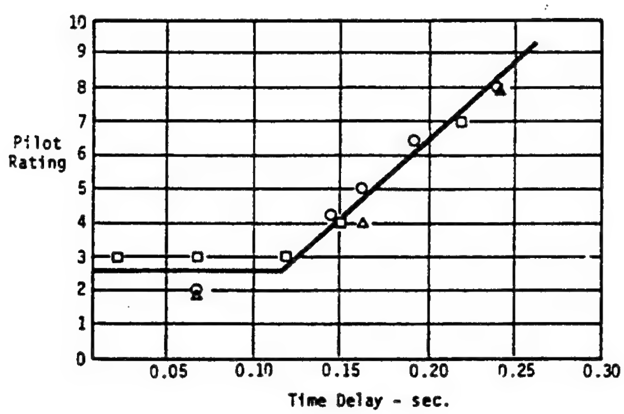

Figure 3: Effects of Time Delay On Fighter Approach And Landing Pitch Flying Quality

- Flying Quality Cliffs

Degraded aircraft flying qualities due to time delays are often not readily detected due to the "cliff-like" nature of the problem. There can potentially be a very rapid degradation in flying qualities due to small changes in pilot tasking, or piloting technique. For example, in the landing task flying qualities problems are often not exposed until the last 50 ft above the runway. Because of the presence of such a cliff, a serious aircraft deficiency might not be detected over repeated evaluations while performing a particular maneuver. Then, due to a subtle change in the task or pilot technique, the pilot can rapidly reach a point where control of the aircraft comes into question. An example of such a flying qualities cliff is the landing of an aircraft with a large time delay. Many passes can be flown in which the aircraft is flown to touchdown with moderate difficulty. If the pilot is required to apply rapid and precise control inputs to compensate for a disturbance such as wind gust, or to make a more precise landing, a full flown PIO can result with potentially disastrous consequences. A real life example of this phenomena occurred during the fifth free flight of the Space Shuttle (Reference 3). On the first four flights, landings were made on Rogers Dry Lake and no significant control difficulties were encountered. The fifth landing, however, was made to a runway of Edwards AFB. Because the task changed to one which required more precision in the touchdown point, the flying qualities precipice was reached resulting in significant pitch oscillations. When the USAF Total In-Flight Simulator (TIFS) was used to simulate the Space Shuttle the longitudinal PIO was also evident (Reference 11). In this case the in-flight simulator provided a more realistic "high stress" task than did the ground based simulators. A realistic stress level is necessary to expose the PIO problem.

- Acceleration Effects

Other flying qualities defects which have been exposed on highly augmented modern aircraft are due to rapid aircraft angular accelerations. Sharp accelerations which are possible with such aircraft are sensed by the pilot causing him to modify his control inputs. In a recent NT-33 study (Reference 5) of lateral aircraft flying qualities it was found that very short roll mode time constants with resultant rapid aircraft roll accelerations degraded a pilot's roll control. The small amplitude, high frequency, jerky roll response commanded by a pilot during precision tasks is often referred to as "roll ratcheting". Another result of rapid accelerations, called "manikin effect", causes coupling between the pilot's arm and the aircraft response. Aircraft accelerations cause inadvertent stick inputs by the pilot which can be stopped only if the pilot releases the stick. This situation is aggravated by sensitive stick gearing like that found on early side stick controllers. Although these difficulties with high accelerations can be detected in airborne simulators where there is an accurate motion environment, they go undetected in even sophisticated ground simulators.

Aircraft Design Process

The difficulties which have recently been exposed in new aircraft with highly augmented control systems point out the need for thorough simulation during the early stages of test and evaluation. Although a great deal of the simulation can be accomplished very effectively with

ground simulators, the use of in-flight simulation should be integrated into the design and test process. A block diagram of the steps necessary during the development of a typical aircraft is illustrated in Figure 4. The process is by necessity an iterative one involving repetitive design, evaluation, and modification phases. The evaluation phases can be accomplished early-on with rudimentary simulation but should develop into sophisticated moving base ground simulation as well as in-flight simulation as the aircraft design is refined. The culmination of this process is, of course, flight testing of the actual vehicle. This step is not only made safer but more cost effective if it is preceded by accurate simulation. A case in point for which this process was properly used, was the development of the YF-17 aircraft which emerged with outstanding flying qualities. The following are several significant points concerning the development of that aircraft.

- The designers created the flight control design using their own design guidelines (not existing design criteria) and a relatively sophisticated ground simulator. Unfortunately, the associated visual display was less than adequate. Even so, it is doubtful if the flying qualities problems would have been exposed with a better display.

- As a result of the near disastrous YF-16 experience, the NT-33 in-flight simulator was utilized for pre first-flight YF-17 evaluations. These evaluations (Reference 2) exposed very serious pitch PIO problems during the final stages of landing.

- Design changes were then implemented and tested on the in-flight simulator and dramatically better flying qualities evolved.

- The YF-17 aircraft with a relatively complex, high authority augmentation system became an aircraft with outstanding flying qualities and is used by the pilots who have flown it as a reference for good flying qualities.

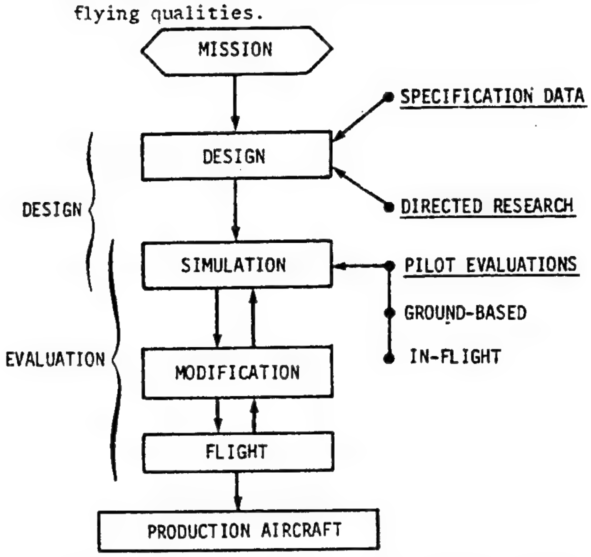

Figure 4: Flying Qualities Development Process

Recent Design Process Deficiencies

Several recent aircraft designs, which did not use ground and airborne simulation to their full advantage, have resulted in vehicles with less than spectacular flying characteristics. The F-16, F-18, and the Space Shuttle have one feature in common: all had serious, and in some cases, dangerous flying qualities problems, exposed well down the development process. Rather than enhancing the aircraft's flying qualities, the advanced control systems often produced dramatic degradation in performance during precision tasks.

One of the most notable recent flying quality design deficiencies occurred with the YF-16. This aircraft was essentially designed on a ground simulator since data for the new side stick controller did not exist. The result was a near disasterous lateral PIO on the first inadvertent flight. One of the problems with the original YF-16 design was the overly sensitive side stick lateral force gradient. This problem had been noted during earlier in-flight simulation using the NT-33 (Reference 2) but was largely discounted as having been due to a poor pilot.

The handling quality deficiencies of the F-18 provide another example in which the design and evaluation phases were not well integrated early in the aircraft's development. The result is that expensive and time consuming design changes have been needed late in the flight test phase. In-flight simulation of the F-18 using the NT-33 was performed just prior to first flight as a final check to enhance first flight safety. The NT-33 in-flight simulation of the F-18's approach and landing characteristics exposed several significant deficiencies even that late in the design process (Reference 8). Results showed that the original yaw augmentation system was unsatisfactory and that the original lateral command gain was too high. In addition, the pitch flying qualities of both the augmented and degraded control system configurations had major flying qualities deficiencies.

These examples of recent aircraft designs show that the evaluation of the flying characteristics of aircraft with complex control systems is not an easy task, and that use of ground and flight simulation is essential to achieve the potential benefits of advanced flight control system technology.

Concluding Remarks

By reproducing the response and feel of other aircraft, an in-flight simulator provides the capability to evaluate new aircraft designs in the flight environment with consequent realism of pilot sensory inputs, tasking, and stress. In-flight simulation should be viewed as complimentary rather than competitive with ground simulation, as each is best suited to a particular aspect of aircraft development. Because of their realism, in-flight simulators can best evaluate flying qualities during critical flight tasks. If only ground simulation facilities are used to evaluate new aircraft, especially those with complex control systems, there is a high risk that major flying quality deficiencies will not be exposed. This has been the case of many of the recent new aircraft designs. Through an understanding of the

important role in-flight simulation can play in the test and evaluation process, many of the recent mistakes can be avoided in the future. The full capability offered by modern flight control technology to create aircraft with outstanding flying qualities can then be realized.

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SIMULATION AS AN ANALYSIS TOOL IN FLIGHT TESTING
A MODIFIED CONTROL SYSTEM ON THE F-14 AIRPLANE

Joseph Gera*
NASA Ames Research Center
Dryden Flight Research Facility
Edwards, California

Abstract

Simulation was extensively used during the flight test evaluation of an experimental lateral-directional stability augmentation system designed for the F-14 airplane in the high angle of attack flight regime. The overall simulation of the test airplane consisted of a full, nonlinear piloted simulation, batch-processed all-digital simulation, and the linear equations of motion at a large number of flight conditions. The benefits of integrating each element of simulation with flight tests are demonstrated by specific examples.

Nomenclature

A_n	normal load factor, g
C_ℓ	rolling moment coefficient
C_{ℓ_β}	effective dihedral parameter, $\frac{\partial C_\ell}{\partial \beta}$, per deg
C_n	yawing moment coefficient, per deg
C_{n_β}	directional stability derivative, $\frac{\partial C_n}{\partial \beta}$, per deg
$C_{n_{\beta_{dyn}}}$	$= C_{n_\beta} \cos \alpha - \left(I_z/I_x\right) C_{\ell_\beta} \sin \alpha$
c.g.	center of gravity
h	altitude, m
I_x, I_z	moments of inertia about the X- and Z-axes, kg-m^2
Im(s)	imaginary part of complex variable s
j	imaginary number, $\sqrt{-1}$
K	ratio of rudder and differential tail deflection, δ_r/δ_a
LCDP	lateral control departure parameter, (Eq. (1))
M	Mach number
MAC	mean aerodynamic chord
p, q, r	angular velocities about the X-, Y-, and Z-axes, respectively, deg/sec
$\bar{q}$	dynamic pressure, N/m^2
Re(s)	real part of complex variable s
$\dot{r}$	angular acceleration about the Z-axis, deg/sec^2
t	time, sec
t_{40}	time to reach a 40 deg/sec yaw rate, sec
α	angle of attack, deg
β	angle of sideslip, deg
δ_a	differential tail deflection, deg
δ_{a_p}	lateral stick deflection, cm
δ_e	horizontal tail deflection, deg
δ_{e_p}	pitch stick deflection, cm
δ_r	rudder deflection, deg
δ_{r_p}	rudder pedal position, cm
δ_{t_p}	thrust lever position, deg
φ	roll angle, deg

Subscript:

max	maximum

*Aerospace engineer

Introduction

Simulation was an essential tool during the design, development, and the joint NASA/Navy flight test evaluation of an experimental stability augmentation system for the F-14 airplane. This experimental system was designed to incorporate a number of control system techniques, each of which was aimed at improving the handling qualities of the airplane at high angles of attack. Reference 1 contains a detailed account of the design criteria and of the use of a major NASA simulator, the Differential Maneuvering Simulator of the Langley Research Center, during the design phase of the control system. Simulation played equally important roles during the final control system development and the flight test evaluation phases.[2] During the control system development and flight test evaluation phases a relatively simple, fixed-base simulation located at the Dryden Flight Research Facility was utilized in direct support of the flight test activities. This support, which consisted mainly of flight planning and crew training, is the topic of another paper at this symposium.[3] The present paper discusses the role of the same simulator as an analysis

tool during high angle of attack flight testing. A brief description of the overall simulation of the test airplane is followed by examples of the use of the simulation for analysis; the analysis either accompanied or followed the actual flight tests. Although the examples are drawn from tests of the high angle of attack handling qualities of an F-14 airplane equipped with an experimental stability augmentation system, this paper is presented with the intention of showing the general benefits of the close interrelationship of flight testing, simulation, and analysis.

Piloted Simulation of the Test Airplane

Flight testing at the Dryden Flight Research Facility is normally supported by some kind of simulation, which can range from a very complex, piloted, hardware-in-the-loop or "iron bird" simulation to a relatively simple digital computer simulation of the test airplane. During the first phase of the flight test evaluation of the experimental high angle of attack control system, the simulation of the F-14 airplane combined an all-digital simulation of the equations of large-amplitude motion and the nonlinear sensors and actuators with a high fidelity simulation of the experimental control system. This simulation was driven by a fixed cockpit incorporating a programmable stick force-feel system, instrument and annunciator panels, spin recovery system, and engine stall warning system panels that closely approximated these installations on the test airplane. Both the simulation hardware and software had provisions for beginning simulation runs from arbitrary initial conditions; the initial conditions could be either trimmed or untrimmed. The automatic capture of initial conditions during a simulation run was another useful feature of this simulator. Reference 3 describes the simulator in greater detail as well as the procedures by which it was refined, validated, and utilized.

The departure and spin resistance of the F-14 airplane, equipped with the experimental lateral-directional stability augmentation system (SAS), was investigated by studying the response of the airplane to intentional, gross misapplications of the pilot controls. Even though the approach adopted for this flight test program was to progressively increase the duration and the amplitude of the misapplied controls, the possibility of prolonged out-of-control flight or a hazardous spin situation had to be considered. Consequently, before the actual flight tests the simulator was used to determine both the limits or boundaries of controllable flight and the best recovery procedures so that upon reaching the limits of control the pilot would immediately apply the most effective recovery controls. Figure 1 shows the relative effectiveness of five types of recovery controls. The boundaries shown are the result of a large number of simulator runs in which a departure was deliberately induced to the right (it should be noted that departures could be induced only after the experimental lateral-directional SAS was disabled). After capturing the appropriate initial conditions, in subsequent simulation runs the pilot applied each type of recovery control and noted the resulting yaw acceleration. The figure shows that the most effective recovery control by far is differential tail deflection applied in the direction of the initial yawing motion. Some additional benefit is derived from the application of aft stick, provided that at the instant of the control input the yaw rate is in excess of 63 deg/sec. Based on these results one of the criteria that required recovery from departures was established at a conservative value of 50 deg/sec during most of the flight tests. Correlation of simulation and flight test results was made difficult by the fact that the highest yaw rate encountered during the control system departure susceptibility test was only 53 deg/sec in one of the more violent intentional departures.

To prepare the pilot for the response of the F-14 to intentionally misapplied controls, the project pilot practiced each evaluation maneuver thoroughly on the simulator before actual flight. This enabled him to anticipate the motion of the airplane in even the more violent maneuvers, during which uncommanded accelerations due to coupling were frequent. An example of an uncommanded normal acceleration due to the interchange of sideslip and angle of attack is shown in Figure 2 in similar maneuvers performed on the simulator and in flight.

During the test program, the simulation of the test airplane was used most frequently in support of the upcoming flight activities or for the analysis of problems encountered in previous flights. In some cases, however, the high fidelity simulator was used in lieu of flight to perform a preliminary analysis of the effect of varying a certain parameter. Figure 3 shows the effect of changing gross weight and center of gravity location on lateral control-induced departures. This brief study showed that in the middle of the center of gravity range increased gross weight resulted in higher departure susceptibility. Aft movement of the center of gravity also increased the departure tendency. Although these simulator predictions have not been verified in flight, previous experience with the simulation gives the author considerable confidence in these results.

Nonlinear Batch-Processed Simulation

The second element of the overall simulation of the test airplane consisted of an unmanned six-degree-of-freedom, nonlinear simulation implemented in a digital computer program. In this program approximately 90 percent of the software was identical to the software developed for the real time, piloted simulator. Newly developed software modules consisted of a driver program (which replaced the cockpit of the piloted simulator) and a plotting package. This unmanned simulation program or batch simulation could be run on the same computer as that used for the real time simulation, but without requiring the F-14 cockpit or any of the associated signal processing hardware. Thus, the setup time was considerably shorter than for simulation runs which required a human pilot. Batch simulation was used in many runs during the simulation validation and aerodynamic data refinement. Figure 4 compares flight data with batch simulation data that resulted from identical pilot inputs. The simulator data compares favorably with the flight data even during the large-amplitude maneuver shown in the figure. The repeatability and the absence of analog-to-digital conversion errors make this type of simulation particularly suitable for fine tuning the aerodynamic data package.

The batch simulation was very important in generating linearized models of the test airplane at any flight condition of interest. This was accomplished by first trimming the nonlinear simulation at the desired condition and then obtaining the dimensional stability and control derivatives by numerical differentiation. In addition to straight and level

flight, trim solution simulating a steady pullup could be obtained at a prescribed altitude, angle of attack, and angle of sideslip. The linearized models were able to reproduce characteristics of the nonlinear motion to a remarkable extent, as illustrated in Figure 5 by the responses to a rudder pedal pulse.

Linear Simulation and Analysis

The third element in the simulation of the test airplane consisted of the linear equations of motion, which were derived from the stability and control derivatives obtained by numerically differentiating the nonlinear equations of motion at various trim conditions. The differential equations of rigid body motions were then augmented by linear models of the power actuators, SAS servoactuators, and the control system. The resulting linear systems were frequently analyzed throughout the flight program by means of a versatile linear control system analysis computer program (which is described in Ref. 4). It is noteworthy that all three elements of the simulation and the analysis program are installed on the same digital computer. This facilitates data exchange and minimizes software development time, since most of the software modules are common to all three elements of the simulation.

The following example illustrates the usefulness of having a simulation capability available during flight test. During the flight test demonstration of the experimental lateral-directional SAS, a relatively mild directional divergence was noted at low subsonic speeds and at an angle of attack of approximately 30°. After some adjustment of the rolling moment data tables, the nonlinear simulator was able to reproduce the time history observed in flight. Subsequent linearization at the same flight condition yielded the lateral-directional equations of motion, which were augmented by the control system dynamics. Varying the gain of roll rate feedback to differential tail produced the root locus plot shown in Figure 6. The figure shows that any attempt to damp the lightly damped Dutch roll mode drives the augmented spiral mode into the zero located on the positive real axis. In fact, errors in the Mach number measurement tended to increase the magnitude of the Mach number-scheduled roll rate-to-differential tail gain, thus causing the control-induced directional divergence. A simple scheduling change in the control system alleviated the problem. Furthermore, the linear analysis indicated accurately the magnitude of the gain to be used for the next flight.

For small control inputs and sideslip angles, and for angles of attack up to 30°, the linear solution appears to be a good approximation of both the flight test data and the nonlinear simulator results. Consequently, an attempt was made to utilize the linearized equations of motion for examining the validity of some of the proposed departure/spin criteria for the augmented F-14. The criterion proposed by Weissman[5] is shown in Figure 7, where $C_{n_{\beta_{dyn}}}$ and the lateral control departure parameter, LCDP, plane is divided into four regions. Since the experimental lateral-directional SAS had a lateral stick-to-rudder interconnect feature, the LCDP was computed by the formula

$$\mathrm{LCDP} = C_{n_\beta} - C_{\ell_\beta} \frac{C_{n_{\delta_a}} + KC_{n_{\delta_r}}}{C_{\ell_{\delta_a}} + KC_{\ell_{\delta_r}}} \tag{1}$$

where K is equal to the differential tail-to-rudder interconnect ratio. According to the figure, the Weissman criterion predicts mild initial yaw divergence followed by roll reversal above an angle of attack of 28°.

Responses of the airplane to full lateral stick inputs are shown in Figure 8. At an angle of attack of approximately 28° the airplane exhibits a slow but positive response to full lateral stick inputs with no tendency to depart or roll in the direction opposite to the command. The apparent contradiction between actual and predicted behavior stems from the fact that the criterion considers only the static aerodynamic characteristics. The experimental lateral-directional SAS altered not only the dynamic characteristics, but to some extent the static characteristics as well. Consequently, the Weissman criterion may be interpreted as an indication of the necessity of stability augmentation or maneuver limiting devices for certain values of $C_{n_{\beta_{dyn}}}$ and LCDP at high angles of attack.

Another departure susceptibility criterion is proposed in Reference 6 by Bihrle. This criterion is similar to the Weissman criterion in that only the static aerodynamic characteristics are taken into consideration. Figure 9 shows the Bihrle criterion applied to the test airplane in an external stores configuration. The criterion predicts that the airplane is susceptible to departures at angles of attack greater than 25°. The departure boundary shown in the figure was established by Bihrle from responses of general fighter airplane simulation to a full control deflection maneuver applied in a trimmed 60° bank angle turn at 35,000 ft (11,500 m) and a Mach number of 0.9. Departure was defined if the angle of attack peak prior to neutralizing the controls exceeded the maximum trim angle of attack by 10°. During the flight test program aggravated control inputs were applied at angles of attack considerably higher than the 25° departure boundary indicated by the Bihrle criterion. In all cases the augmented airplane was highly resistant to departures. Figure 10 shows a maneuver performed by the test airplane similar to the evaluation maneuver used by Bihrle. Despite the predicted departure, the augmentation system succesfully limited the maneuver to be relatively mild, even though the pilot held the full lateral stick input nearly 2 seconds longer than the 8 seconds used in Reference 6. The peak angle of attack of 40° is about 4° higher than the maximum trim angle of attack of the F-14 in the configuration flown. Rather than a roll departure opposite the lateral control, the actual response shows a slow rolling motion out of the turn in the direction commanded by the full left stick deflection. The rudder deflection seen in the figure was entirely due to the lateral stick-to-rudder interconnect employed by the control system.

The linear analysis package of the overall simulation lent itself to the examination of a third proposed departure susceptibility criterion.[7] Application of this criterion required linearization about a trim solution at various angles of attack and nonzero sideslip in order to obtain the coupled longitudinal and lateral-directional equations of motion. The eighth-order

linear system was augmented by the control and actuation system. The criterion of Reference 7 was applied to the resulting eighteenth-order linear system. This involved the computation of the zeros of the φ/δ_{a_p} transfer function at high angles of attack. No zeros were found in the right hand plane at angles of attack below 28°. At 28° and 31° of angle of attack the numerator zeros were $0.05 \pm 0.2083j$ and $0.094 \pm 0.0773j$, respectively, with real parts considerably less than 0.5, the value proposed by References 7 and 8 as the boundary above which departures are likely. Although in this case the criterion correctly predicts the augmented airplane to be departure resistant, the example presented here should not be regarded as a general validation of the criterion.

Concluding Remarks

The angle of attack handling characteristics, including departure and spin susceptibility, of the F-14 airplane equipped with an experimental lateral-directional stability augmentation system (SAS) have been investigated in a joint NASA/Navy flight test program. The simulation of the test airplane was found to be essential during the flight tests in flight planning and in evaluating and analyzing flight data. The simulation consisted of three elements: a full nonlinear piloted simulation, batch-processed all-digital simulation, and a large number of linear models representing the airplane at many different flight conditions. In this paper the utilization of each of these elements as an analysis tool is demonstrated by several examples. Specific features of the piloted simulation, such as the capture of initial conditions at any point during a simulation run, allowed the precise comparison of various recovery controls applied in a departure. The comparison showed that for the test airplane the most effective recovery control by far is the differential tail applied in the direction of the yawing motion. A similar simulator study showed that increased gross weight resulted in higher departure susceptibility at the middle center of gravity range. Aft movement of the center of gravity also increased the departure tendency, but at the aft center of gravity position the effect of weight changes was minimal. In addition to studies of this type the simulator was also useful in predicting and analyzing complex, large-amplitude motions.

The second element of the simulation consisted of a batch-processed all-digital simulation which allowed precise comparison of time histories measured in flight with the responses of the simulation. This facilitated the validation of the simulation and the fine tuning of the aerodynamic data package. The batch-processed simulation was also used with a trim and numerical differentiation algorithm to compute the linear equations of motion at a large number of flight conditions.

The linear models of the test airplane constituted the third element of the test airplane simulation. Comparison of the linear system response with that of the nonlinear simulator showed good agreement up to the highest achievable trim angles of attack. During the flight tests the linear system was useful in understanding more completely the effect of adjusting the parameters of the control system, particularly in those regions of the flight envelope where the aerodynamic characteristics are rapidly changing. The linear system analysis package integrated with the simulation program allowed the application of three proposed departure susceptibility criteria. This showed that criteria based solely on static aerodynamic characteristics cannot predict the departure characteristics of the highly augmented test airplane but may indicate correctly regions of the flight envelope where stability augmentation or maneuver limiting is needed.

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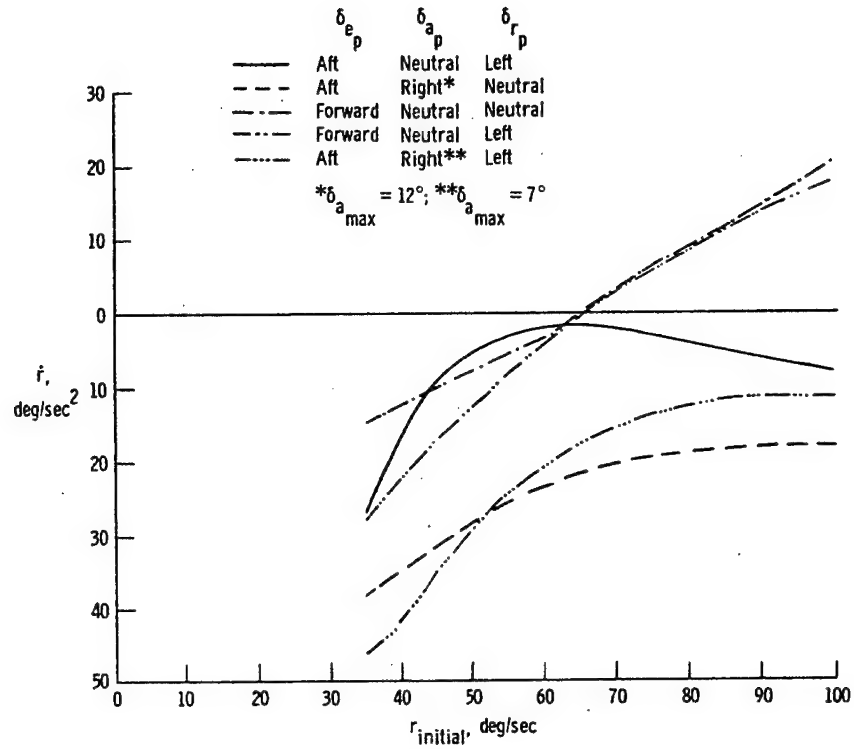

Fig. 1 Relative effectiveness of various recovery controls from an initial positive yaw rate during simulated intentional departures.

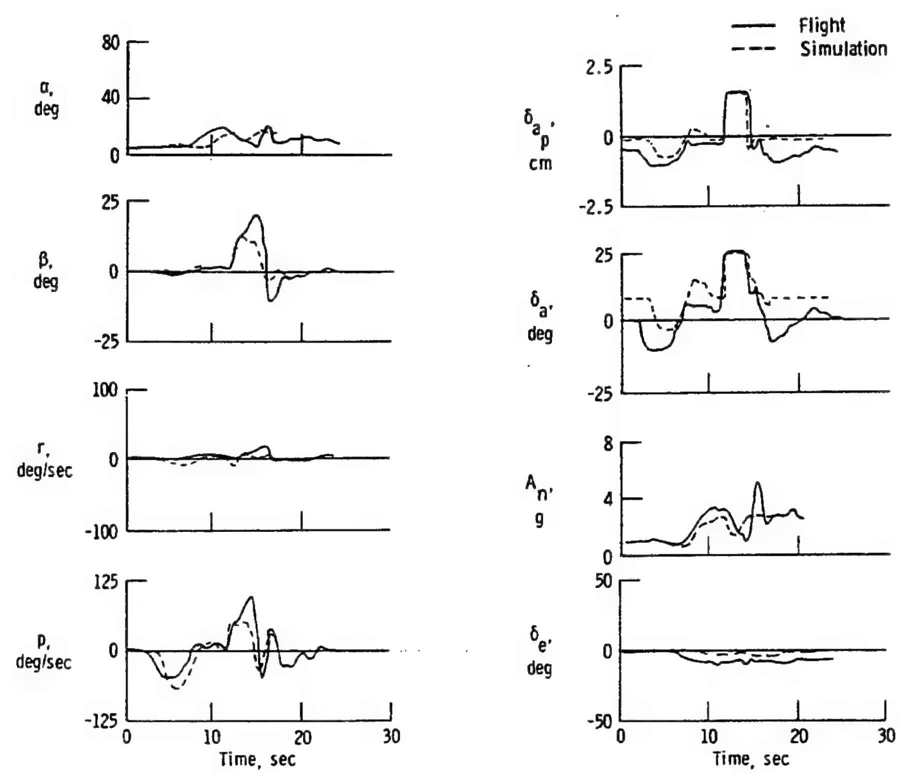

Fig. 2 Time history of kinematic coupling in cross-control maneuver. $M = 0.8$, $\alpha_{initial} = 18°$, $h = 12,192$ m.

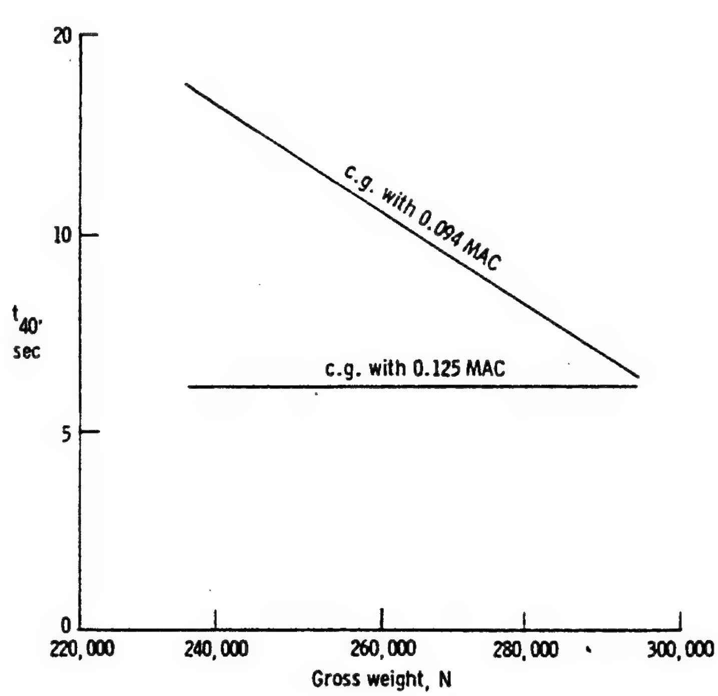

Fig. 3 The effect of gross weight and center of gravity location on lateral control induced departures.

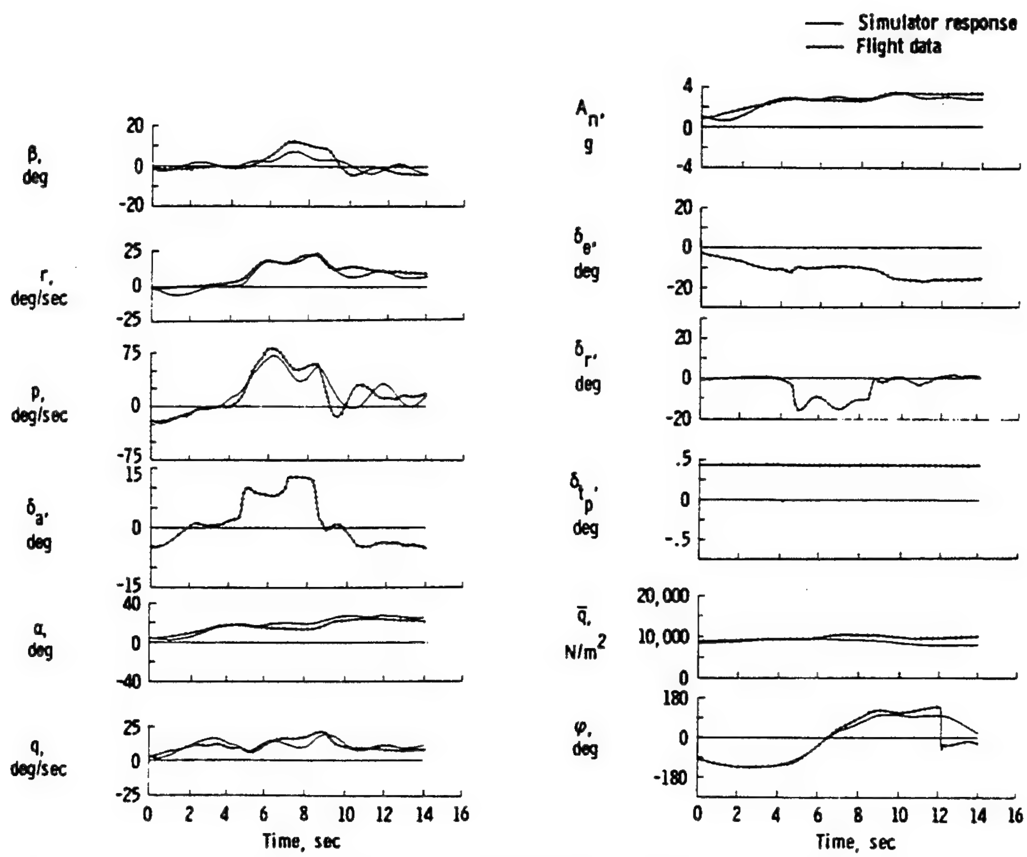

Fig. 4 Comparison of the simulator response with flight data obtained with identical control surface displacements.

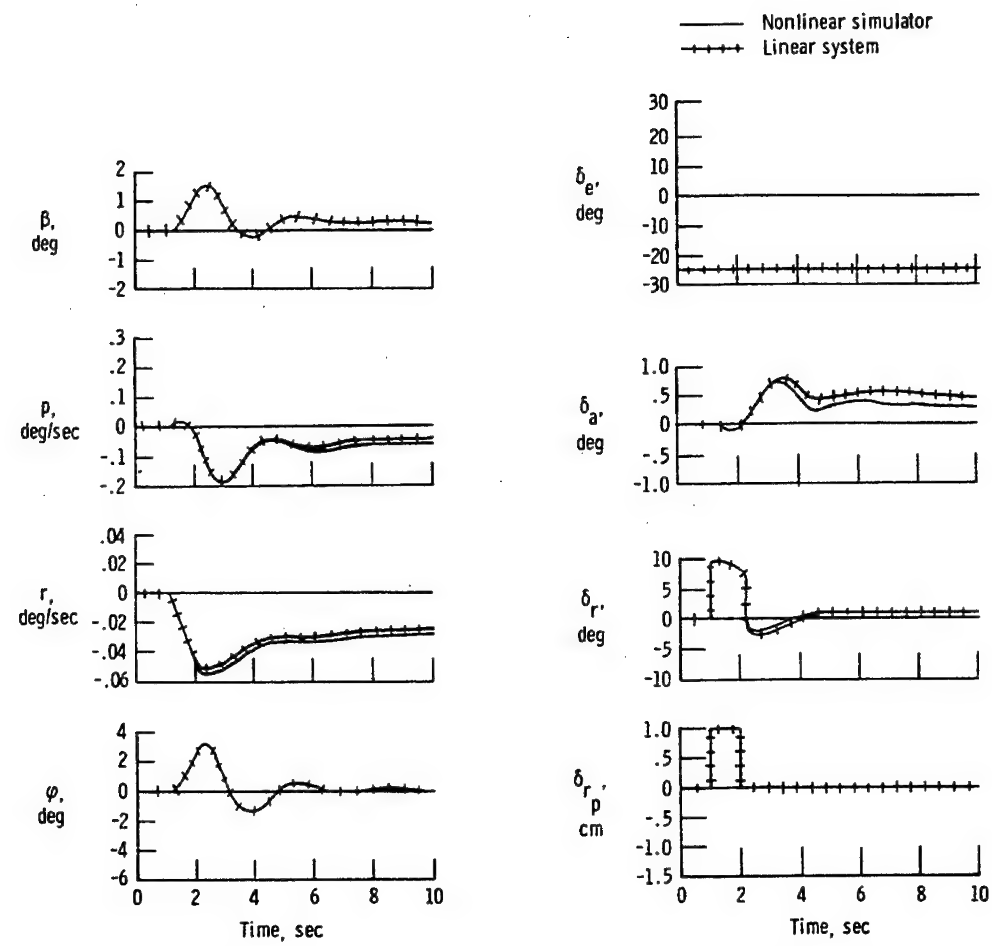

Fig. 5 Comparison of the responses of the nonlinear simulator and of the linear system to a rudder pedal pulse. $M = 0.7$, $\alpha = 25°$, $h = 12,300$ m.

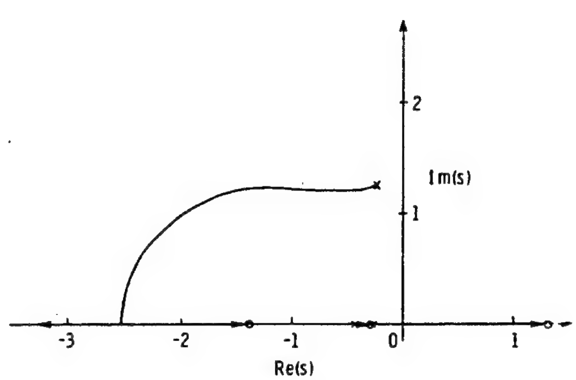

Fig. 6 Root locus resulting from varying the roll rate-to-differential tail feedback gain. $M = 0.6$, $\alpha = 27°$, $h = 11,500$ m.

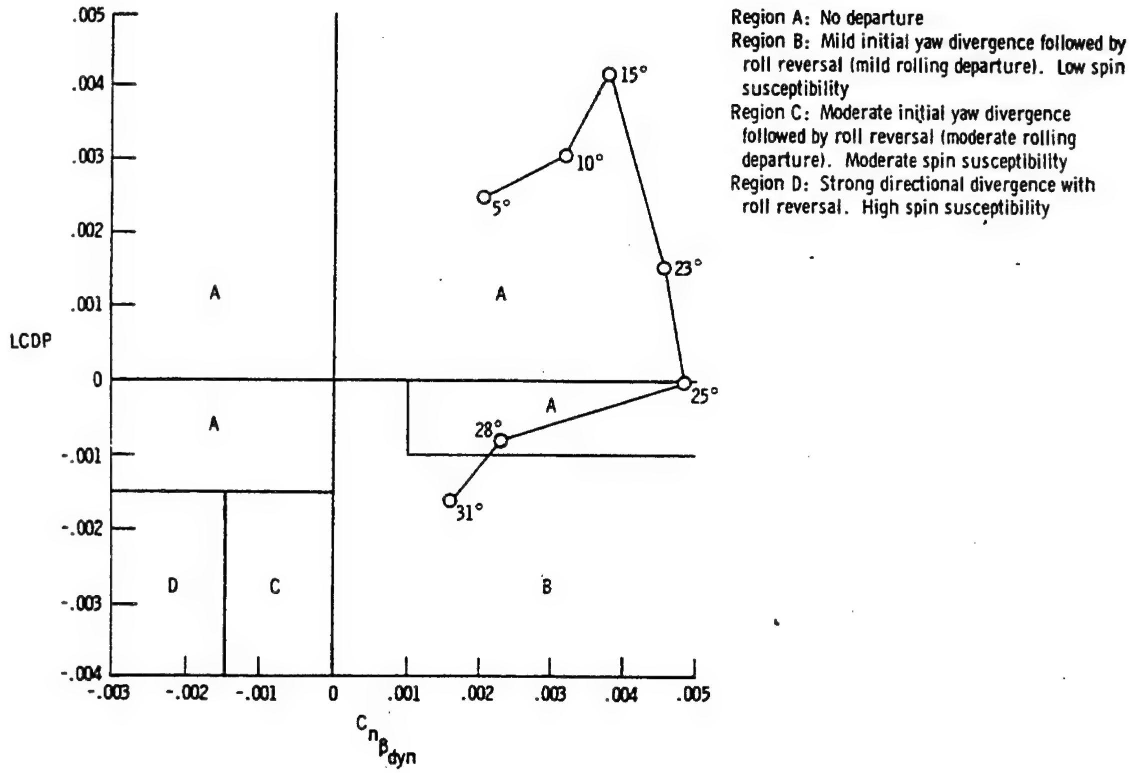

Fig. 7 The Weissman criterion prediction of departure susceptibility of the test airplane at M = 0.6.

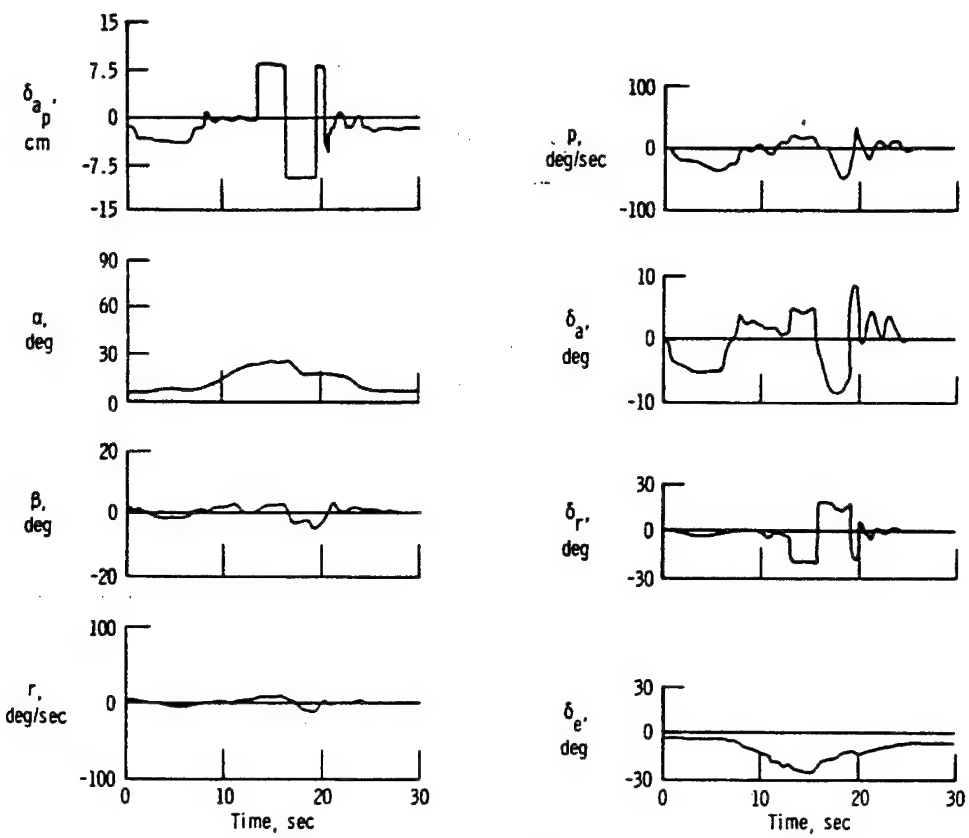

Fig. 8 Full lateral stick step inputs at high angles of attack. M = 0.64, h = 11,500 m.

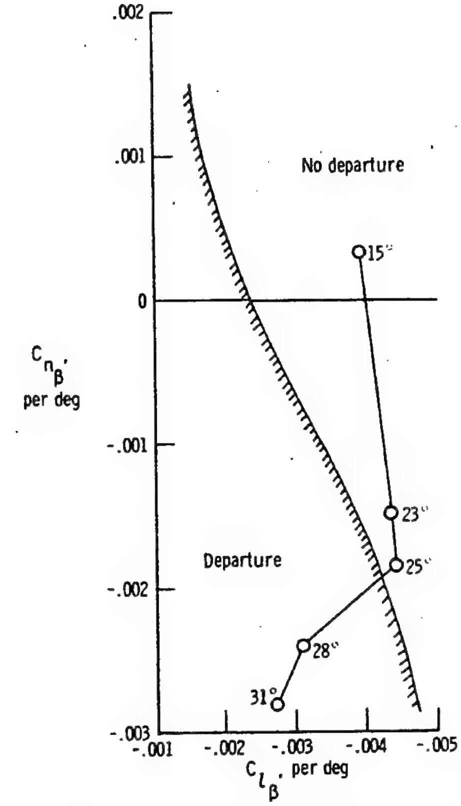

Fig. 9 The Bihrle criterion prediction of the departure susceptibility of the test airplane.

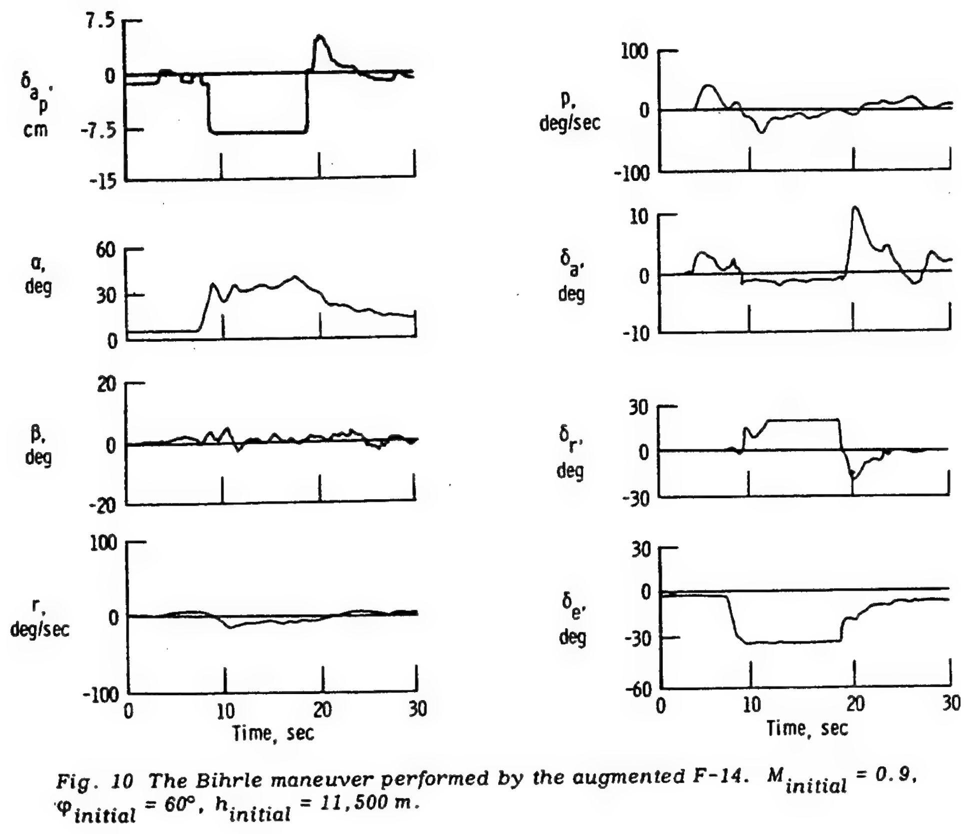

Fig. 10 The Bihrle maneuver performed by the augmented F-14. $M_{initial} = 0.9$, $\varphi_{initial} = 60°$, $h_{initial} = 11,500$ m.

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SIMULATION OF THE XV-15 TILT ROTOR RESEARCH AIRCRAFT

Gary B. Churchill*
U. S. Army Aeromechanics Laboratory
Moffett Field, California

and

Daniel C. Dugan†
Ames Research Center, NASA
Moffett Field, California

Abstract

The XV-15 Tilt Rotor Research Aircraft Program (TRRA) exemplifi s the effective use of simulation from issuance of the request for proposal through conduct of a flight test program. From program inception, simulation complemented all phases of XV-15 development. The initial simulation evaluations during the source evaluation board proceedings contributed significantly to performance and stability and control evaluations. Eight subsequent simulation periods provided major contributions in the areas of control concepts, cockpit configuration, handling qualities, pilot workload, failure effects and recovery procedures, and flight boundary problems and recovery procedures. The fidelity of the simulation also made it a valuable pilot training aid, as well as a suitable tool for military and civil mission evaluations. Recent simulation periods have provided valuable design data for refinement of automatic flight control systems. Throughout the program, fidelity has been a prime issue and has resulted in unique data and methods for fidelity evaluation which are presented and discussed.

Introduction

The XV-15 Tilt Rotor Research Aircraft program is a joint Army/NASA/Navy program initiated in 1973 as a "proof-of-concept" and "technology demonstrator" program for the tilt rotor V/STOL aircraft concept (Navy participation began in 1979). Two aircraft were built by Bell Helicopter Textron, and basic proof-of-concept flight testing was completed in September 1981. At present, one aircraft is at Ames Research Center for continuation of government flight testing for aircraft documentation, and the other is at Bell Helicopter Textron for further contractor development and participation in military applications demonstrations. Significant program milestones are shown in Fig. 1.

The tilt-rotor concept is relatively complex and, based on other V/STOL aircraft history, was considered to be a high-risk program. Therefore, from program conception, comprehensive piloted simulation was made an integral part of the design, development, and test programs. Starting with parallel simulation of the bidders' design proposals, and continuing through October 1981, simulation was integrated with the entire flight test program. Before first hover tests of the XV-15 in May 1977, four major simulations and one limited simulation were conducted at Ames Research Center. The major simulations utilized the Flight Simulator for Advanced Aircraft (FSAA), and the limited hover simulation was performed on the Six-Degree-of-Freedom simulator. Since the beginning of the contractor's flight test program in April 1979, four additional major simulations have been performed to investigate flight-test anomalies, systems refinement, and military missions evaluations. Three utilized the FSAA, and one utilized the new Vertical Motion Simulator (VMS). These simulation periods were also used to provide pilot training and

*Handling Qualities, Flight Controls, and Simulation Specialist, Tilt Rotor Research Aircraft Project.
†XV-15 Project Test Pilot.

• CONTRACT SIGNED	JULY 1973
• NO. 1 XV-15 ROLLOUT	OCTOBER 1976
• GROUND TIE-DOWN TESTING	JANUARY-MAY 1977
• HOVER TESTS (AIRCRAFT NO. 1)	MAY 1977
• WIND TUNNEL TESTS (AIRCRAFT NO. 1)	MAY-JUNE 1978
• CONTRACTOR FLIGHT TESTS (NO. 2)	APRIL 1979-JULY 1980
• GOVERNMENT ACCEPTANCE (NO. 2)	OCTOBER 1980
• GOVERNMENT FLIGHT TEST	JANUARY 1981-CONTINUING
• PARIS AIR SHOW (NO. 1)	JUNE 1981
• CONTRACTOR DEVELOPMENT (NO. 1)	OCTOBER 1981-CONTINUING

Fig. 1 XV-15 aircraft program chronology.

familiarization in addition to satisfying the research objectives.

Since the piloted simulation efforts were considered to be a critical element of the program, the overall fidelity of the simulation was of prime importance. The required fidelity was obtained by close attention to mathematical model integrity, as well as to fidelity issues related to normal simulation problems. These included motion and visual systems and correlation with actual flight characteristics of the aircraft. This report presents the manner in which the XV-15 simulation was developed to provide the required fidelity, its use throughout the program, its limitations, and an assessment of its value relative to program performance and safety.

XV-15 Design Characteristics

A brief description of the XV-15 tilt rotor will help to define the scope and complexities of the simulation model. The aircraft hovers and operates in low-speed flight as a lateral-tandem-rotor helicopter, with that vehicle's attendant stability and control requirements (Fig. 2).

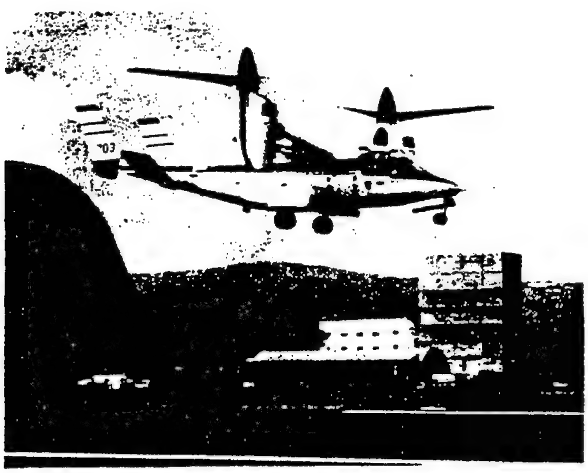

Fig. 2 XV-15 in helicopter mode.

It also flies as a high-performance, turboprop airplane with conventional control surfaces (Fig. 3).

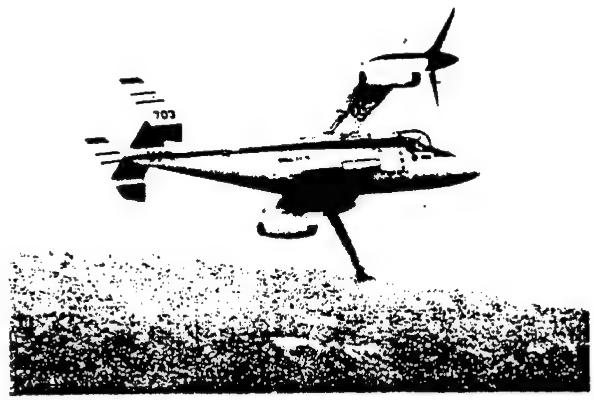

Fig. 3 . XV-15 in airplane mode.

In between modes, it uses a combination of rotor and conventional airplane controls, for it derives lift from both the rotors and the wing. Control phasing is accomplished mechanically with control-system gains varying with nacelle tilt and airspeed.

The XV-15 is powered by two Lycoming T-53 turboshaft engines, designated LTC1K-4K, which are rated at 1,550 shp for takeoff with a normal rating of 1,250 shp. A transmission cross-shaft permits both rotors to be driven by one engine. The engines, transmissions, and rotor systems are located in wing-tip nacelles which can be rotated 95°—from 0° in the airplane mode to 5° aft of vertical in the helicopter mode. The three-blade proprotors are 25 ft in diameter and the blade twist is 45° from root to tip. They are gimbal-mounted to the hub with an elastomeric spring for control augmentation. The wing span is 32 ft from spinner to spinner, and the aircraft is 42 ft long (Fig. 4). Wing loading is 77 lb/ft^2, and disc loading at the design gross weight of 13,000 lb is 13.2 lb/ft^2. The XV-15 carries 1,475 lb of fuel, which allows a research flight of about 1 hr. It is equipped with LW-3B rocket seats for the crew of two.

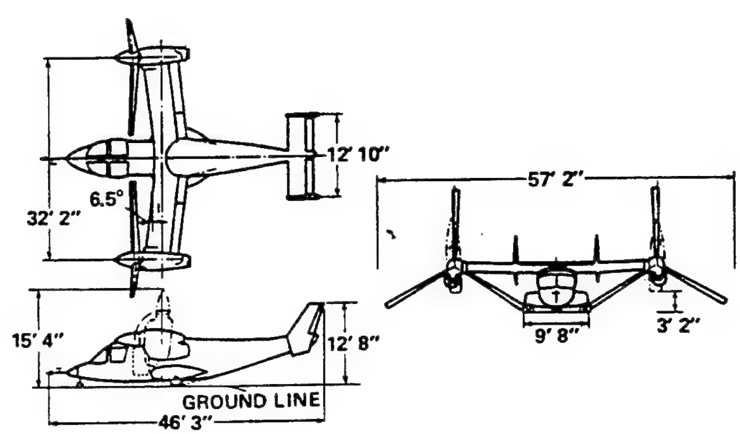

Fig. 4 XV-15 dimensions.

In the helicopter mode, the XV-15 flight control system can be compared to that of a lateral-tandem helicopter. The use of collective pitch, cyclic pitch, differential cyclic, and differential collective are shown in Fig. 5. During hovering flight, the airplane control surfaces are active but are ineffective at low speeds. Rotor controls are mechanically phased out as the conversion process progresses to the airplane mode and the conventional elevator, flaperons, and rudders generate control moments. Full-span, electrically operated flaps are used during hover and in the conversion modes. A schematic of the flight-control system is presented in Fig. 6.

Rotor rpm is maintained by a blade-pitch governor, which detects error between commanded and actual rpm. Collective-pitch inputs from the dual-channel governor are superimposed on collective-pitch inputs from the power lever and lateral stick

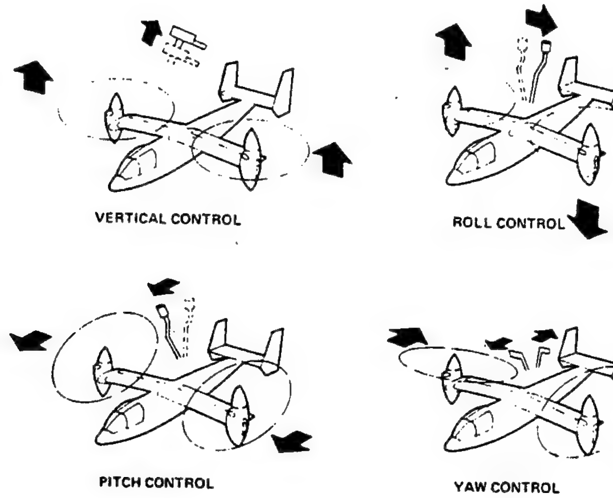

Fig. 5 Helicopter mode control functions.

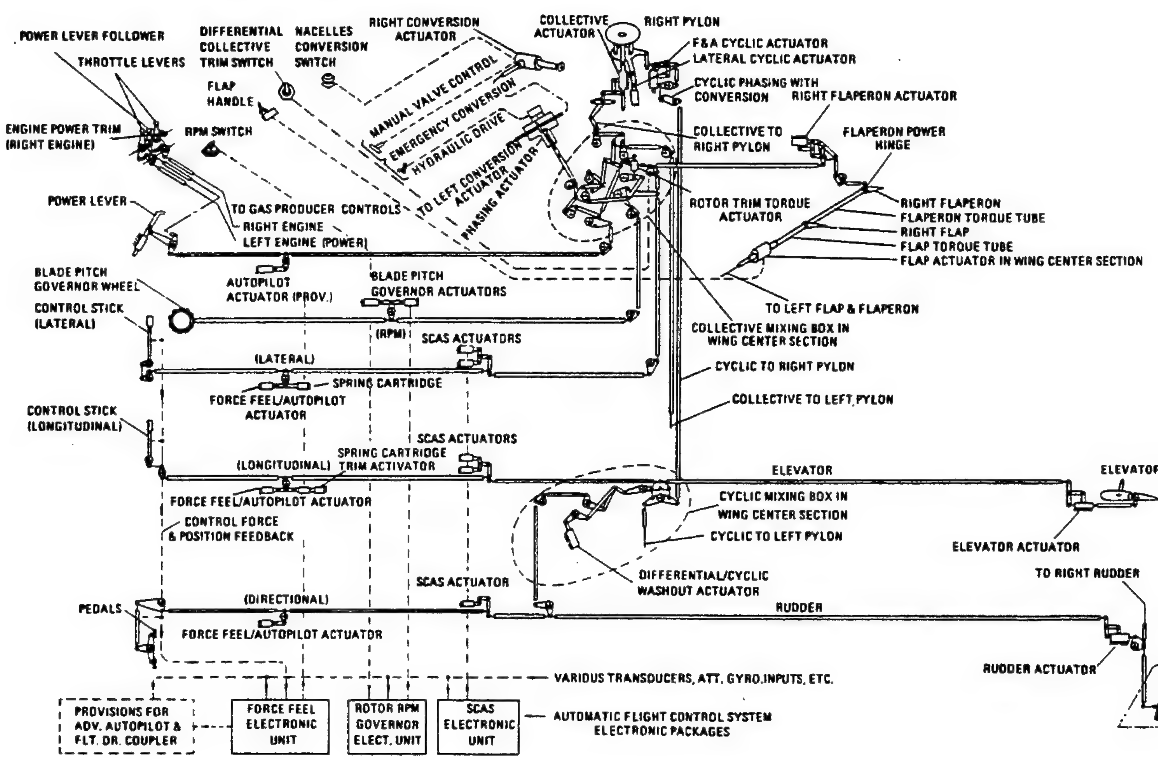

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Fig. 6 Flight control system schematic.

in the helicopter mode. Total collective-pitch authority is transferred to the governor during conversion to airplane mode. A manual control wheel in the cockpit may be used for rpm control should the governor fail.

Stability and control augmentation (SCAS) is provided by a three-axis rate system with a pitch and roll attitude retention feature. SCAS gains are varied with conversion angle to provide appropriate rate damping and control augmentation for either helicopter or airplane mode flight. Pitch and roll axes have dual channels, and the yaw axis is single channel. SCAS-off flight has been routinely demonstrated; damping and control are degraded, but the XV-15 is quite safe to fly, even though the pilot workload is significantly higher. A force-feel system (FFS) provides stick and pedal forces proportional to control displacements while isolating the pilot controls from SCAS feedback forces. Force gradients are increased and trim rates are decreased with airspeed through a dynamic pressure ("q") sensor. With FFS off, pitch trim is available at a reduced rate; control forces are high but manageable.

An interconnected, hydraulically powered conversion system (Fig. 7) provides 95° of nacelle tilt at a rate of approximately 7.5°/sec. A continuous conversion can be accomplished in about 12 sec, or the pilot can perform the conversion in steps or at a slower rate of 1.5°/sec. Hydraulic power for conversion is triply redundant because the XV-15 cannot be landed in the airplane mode. In the event of total electrical failure, the pilot still has mechanical access to hydraulic power to convert to the helicopter or STOL mode.

The current airspeed-altitude envelope is shown in Fig. 8. Some of the level-flight stabilized points are plotted along with the predicted envelope based on the normal rated power and torque limits.

Additional details of the XV-15 design are given in Refs. 1 through 4.

Simulation Description

The simulation facilities at Ames Research Center are designed to provide research simulation capability for a wide variety of aircraft concepts, ranging from helicopters and V/STOL aircraft to supersonic transports and the Space Shuttle. These facilities are operated and maintained by the Flight Systems and Simulation Research Division of the Aeronautics and Flight Systems Directorate. The active time required for any one simulation on a major facility (FSAA or VMS) varies from several weeks to several months. Figure 9 presents a schematic of the simulation system applicable to any desired configuration.

The elements common to all simulations are the cab and motion system, the visual systems, control loaders, and a host computer, in this case, a Xerox Data Systems (XDS) Sigma 8. Within the host computer, standard software is provided for all equations of motion, transformations, motion and visual drives, etc. The user provides the mathematical model for the aircraft, including all aerodynamics, structural dynamics (if included), flight controls, instrument requirements, and definitions of force-feel system parameters.[5] When done in this manner, a change in configuration from simulation to simulation only requires changing the simulator cab instrument panel and control configuration to that required by the user, installing and checking out the user's mathematical model on the computer, and integrating the desired elements into an operating system. These changes are normally accomplished in about 2 weeks; this includes generating fidelity evaluation data as required by the users. These data normally include such items as static and dynamic checks, visual, force-feel, and motion systems frequency response data, or any other data specified by the user. The evaluations and data requirements used to assess the XV-15 simulation fidelity will be discussed later.

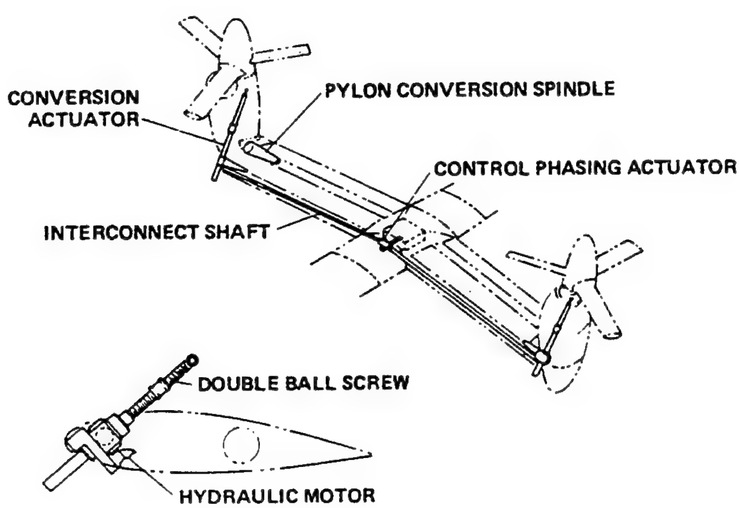


Fig. 7 Conversion system.

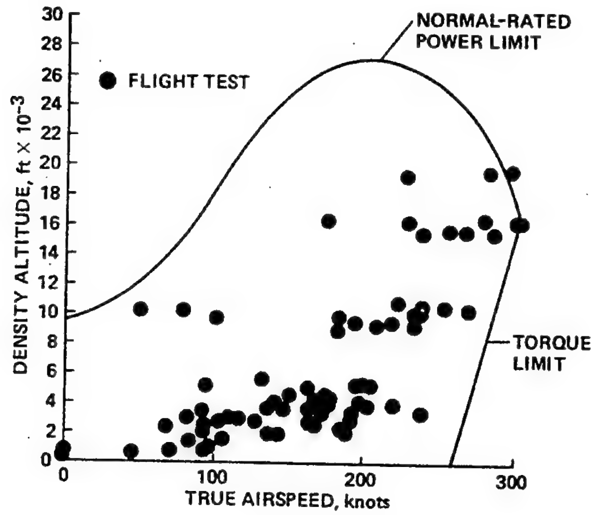


Fig. 8 Airspeed-altitude envelope.

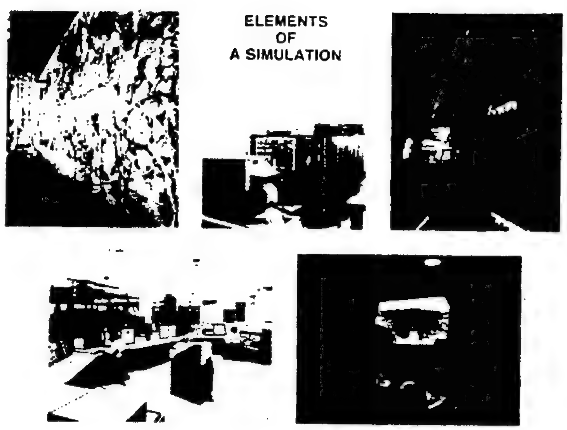


Fig. 9 Simulation elements.

Development

The decision to make piloted simulation a significant and integral part of the Tilt Rotor Research Aircraft (TRRA) program was made in July 1971, before TRRA program approval by NASA and Army Headquarters. The requests for proposals for the mathematical model and simulation development were released in August 1971, with the following ground rules for bidders:

1) A complete nonlinear mathematical model and aircraft simulation was to be developed

2) Modular mathematical model construction in a specified format was to be used

3) The mathematical model was to be programmed and checked out at the contractor's facility, simultaneously with programming and check out at the government's facility (FSAA)

4) The simulation was to be operational on the FSAA in 1 year

Two bidders responded to the request for proposals, Boeing-Vertol and Bell Helicopter Textron (BHT), who were also the only subsequent bidders for the aircraft development.

Although this program was extremely ambitious, both contractors completed their efforts in about 14 months, which was in time to effectively use the simulation during the source evaluation board (SEB) proceedings in March 1973. Both the contractors and the government obtained significant benefits from the simulation development program. The contractors developed an "in-house" simulation for their use in proposal preparation, and the government received a program from each contractor. These programs provided both the contractor's data and analytical methods for evaluating the contractors' performance, and stability and control proposal submittals.

Mathematical Model

A detailed discussion of the XV-15 mathematical model[6] is beyond the scope of this paper. At the time it was developed, it was the largest, most complex ever implemented on the simulation facilities at Ames Research Center. It contains a complete nonlinear representation of the XV-15 aircraft, which includes all aerodynamics through an angle of attack and sideslip range of ±180°, interactions of the rotor wake on the airframe, all flight controls and actuators, the automatic flight controls and the landing gear. The rotor model uses linearized aerodynamics with nonuniform inflow rather than strip analysis, since the latter requires more computer capacity than is available. The rotor model is valid for the full XV-15 envelope, including autorotations. Additional details on nonlinear complex aerodynamic interactions are available in Ref. 7. The total model represents 13 degrees of freedom. Since program inception, the mathematical model document has undergone eight revisions to maintain its status relative to the aircraft configuration and data base. The latest revision was completed in 1980 and represents the present aircraft configuration.

The requirement for a modular structure of the mathematical model was specified to streamline the general programming and to provide simple access to any particular module for changes resulting from variations in the design or from improvements in the data bases. Thus, although each module had a fixed input and output, the modeling within the module could be simplistic initially and increased in complexity as analysis or data justified. The final configuration of the mathematical model[6] contains 20 separate subsystems or modules.

During the early phases of the XV-15 program, Systems Technology, Inc. (STI), Hawthorne, California, provided technical support to the Project Office in the areas of flight controls development and simulation. As a result of these efforts, STI developed an addendum for the BHT mathematical model which provided the additional capability of evaluating the effects of control-system hysteresis and flexibility on aircraft characteristics.[8] This modeling could be switched in or out for evaluations, and was quite valuable in identifying limit-cycling behavior occurring during flight test. The effect of the hysteresis modeling on simulation is discussed in the section on fidelity.

The mathematical model of the XV-15 landing gear was the only significant aircraft element that was compromised in the simulation. This was because the digital simulation cycle times required were far in excess of that required for the high rate of change of forces on the landing gear during touchdown. This problem is also discussed further in the section on fidelity.

A significant portion of the simulation use was devoted to identifying failure effects and recovery procedures, since significant adverse failure effects could require systems redesign. To facilitate these evaluations, systems failures were modeled for single or dual engines, hydraulic systems, electrical systems, stability and control augmentation systems, force-feel systems, and governor systems. These are controlled by the test engineer and are currently used during training and familiarization of new pilots.

The effects of airframe aeroelastics were considered in the contractor development phase by Boeing-Vertol. The modes evaluated were wing vertical bending (3.5 Hz), wing torsion (10 Hz), and wing chord bending (6 Hz). These were evaluated on the contractor's simulation facility, where it was determined that the only mode affecting the pilot control task was wing vertical bending. This occurred only in hovering flight, and the net effect was to cause an approximate 0.1-sec lag in vertical response to control. Since this lag is approximately the same as that induced by digital simulation cycle-time lag, further considerations of aeroelastics were deleted.

Simulation Hardware

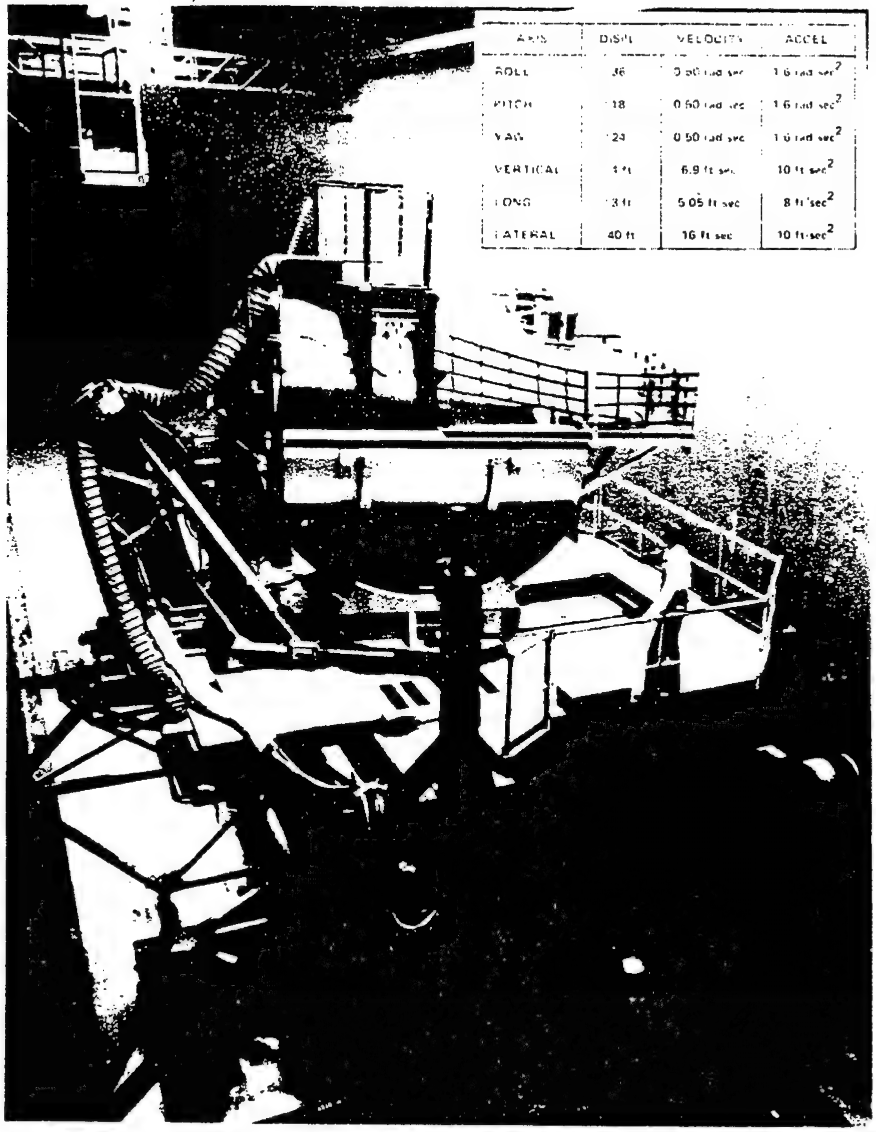
During the course of the XV-15 program, three of the simulators at Ames Research Center were used: the Flight Simulator for Advanced Aircraft (FSAA), the Vertical Motion Simulator (VMS), and the Six-Degree-of-Freedom Motion Simulator (6-DOF). The FSAA and VMS simulations were essentially identical, with the exception of the motion systems. The 6-DOF simulation utilized a simplified perturbation-type mathematical model applicable only to hover and low-speed flight (0-10 knots).

Flight Simulator for Advanced Aircraft. The FSAA has been the workhorse of the XV-15 simulation program (Fig. 10). It permitted large-amplitude motion and rapid accelerations for the many tasks and evaluations performed. The cab is provided with a virtual image television visual which presents a visual scene from one of two large terrain boards. These boards provided a typical airport and runway environment, a STOL port, carrier or other ship models for landing, a nap-of-the-earth terrain area for low-level flight around vegetation and hills, and other features to enhance the realism of the simulation. Provisions for instrument flight to minimums were available, as well as flight "on top" to escape the confines of the terrain-board boundaries. Other aids to the pilot include a Visual Approach Slope Indicator (VASI) light for approaches to the runway. An XDS Sigma 8 digital computer was used to compute the aircraft dynamics. Electro-hydraulic control loaders were used to provide the variable stick and pedal control forces necessary for the simulation. The right side of the two-place cab was set up for the XV-15 with essential controls and instruments. Details of the cockpit will be discussed later.

Vertical Motion Simulator. The VMS was used to examine SCAS and blade-pitch governor modifications designed to improve the response and handling qualities of the XV-15. It is a new and unique simulation facility which includes the capability for 60 ft of vertical motion and 40 ft of lateral travel (Fig. 11). The visual systems, control loaders, and computers used are essentially the same as those used during FSAA simulations.

The Six-Degree-of-Freedom Motion Simulator. The 6-DOF simulator has a single-place cab and is well suited for the evaluation of VTOL aircraft in hovering flight (Fig. 12). Helicopter controls were used for this limited evaluation, and the cockpit was left open to provide a one-to-one visual simulation, using the interior of the facility and the world outside through open hangar doors. The motion system was driven directly from computed aircraft accelerations (no washouts were employed). Therefore, within an 18-ft cube all attitude, motion, and visual cues were real. An early look at some failure modes was accomplished and an automatic system to increase engine power in the event of single-engine failure during hover was eliminated from the design. In all cases, the pilots beat the automatic system with power application.

XV-15 Simulated Cockpit. The cockpit setup for the XV-15 simulations provided the pilots with the essential controls and instruments to effectively simulate the aircraft. The instrument panel of the simulator is shown in Fig. 13 and that of the XV-15 is shown in Fig. 14. The cockpit configuration was identical for both the FSAA and VMS simulations. The instruments, although not identical to those in the aircraft in most cases, were similar and their locations in the simulator closely matched their locations in the XV-15. Many engine, transmission, and systems gages and the caution panel were not functional but only mocked-up in the simulator. The center console of the simulator, partially shown in Fig. 13, incorporated SCAS, FFS, and governor panels which were identical in function and very similar in appearance to the real thing.



AXIS	DISPL	VELOCITY	ACCEL
ROLL	36	0.50 rad/sec	1.6 rad/sec^2
PITCH	18	0.50 rad/sec	1.6 rad/sec^2
YAW	24	0.50 rad/sec	1.6 rad/sec^2
VERTICAL	4 ft	6.9 ft/sec	10 ft/sec^2
LONG	3 ft	5.05 ft/sec	8 ft/sec^2
LATERAL	40 ft	16 ft/sec	10 ft/sec^2

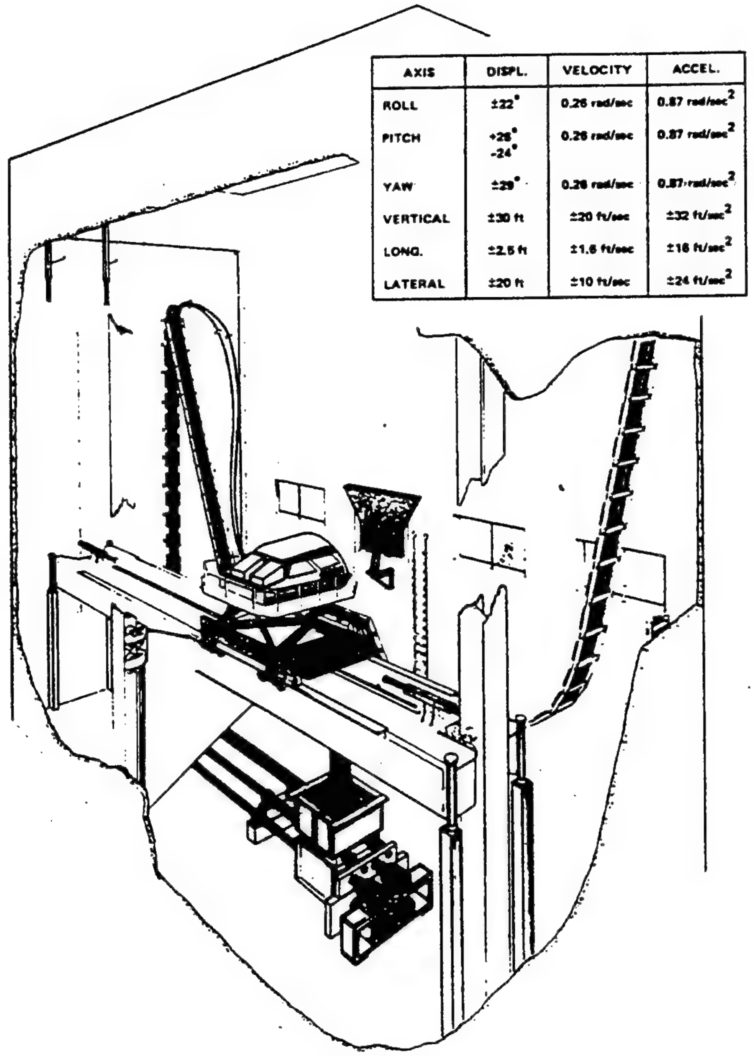
Fig. 10 Flight Simulator for Advanced Aircraft.

The power lever and control stick in the simulator were configured to match those in the XV-15, and they incorporated the same functions and switches in their design. Finally, the landing gear and flap switches were located on the right, aft end of the center console in their proper location. All of this attention to detail was important in the research simulator. This was not only true for the evaluations of the aircraft response and handling qualities, but also for the transfer of training, both deliberate and unplanned, which the pilots would acquire during the simulations before the first flight of the aircraft. Instrument scan, control feel and manipulation, and systems operation during normal operation and failure modes had to be realistic.

Simulation Evaluations

Chronology

The XV-15 simulation chronology is shown in Fig. 15. The initial XV-15 simulation in 1973, conducted on the FSAA, was a comparative evaluation of the two contractors' design proposals for a tilt-rotor aircraft. NASA, Army, and contractor pilots and engineers participated in the evaluation, and the results were considered in "other factors" in the source evaluation process. After the selection of the contractor to build the two tilt-rotor aircraft in July 1973, a limited simulation was conducted on the 6-DOF simulator for some early design analysis. It was followed in December 1973 by an



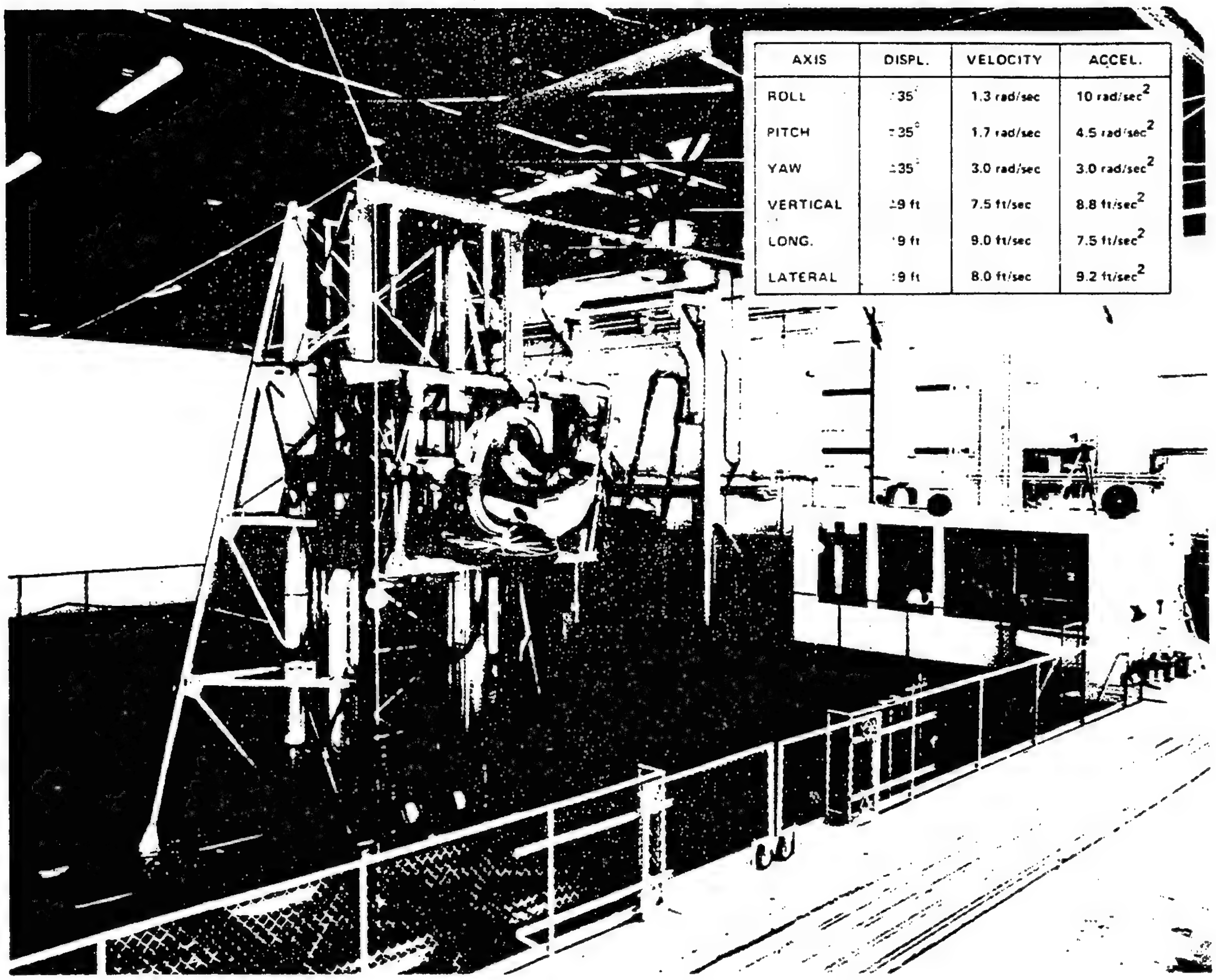
AXIS	DISPL.	VELOCITY	ACCEL.
ROLL	±22°	0.26 rad/sec	0.87 rad/sec^2
PITCH	+26° -24°	0.26 rad/sec	0.87 rad/sec^2
YAW	±29°	0.26 rad/sec	0.87 rad/sec^2
VERTICAL	±30 ft	±20 ft/sec	±32 ft/sec^2
LONG.	±2.5 ft	±1.6 ft/sec	±16 ft/sec^2
LATERAL	±20 ft	±10 ft/sec	±24 ft/sec^2

Fig. 11 Vertical Motion Simulator.

extensive simulation on the FSAA of the selected Bell configuration.[9] The simulation covered control-system and subsystem engineering studies, aircraft handling-qualities investigation, and the cockpit design.

Significant control-system and mathematical model changes resulted from this effort. It was followed in July of 1974 by another major simulation to continue design analysis of the control system and subsystems in normal and failure modes and investigation of predicted handling qualities.[10] Cockpit layout evaluations continued and changes were incorporated. In October 1975 the simulation objectives were to investigate various operational conditions and to look at envelope boundary or limit conditions.[11] Cockpit changes made since the last simulation were also evaluated. Flight boundary conditions included thrust and blade-load limits and wing stall. This completed program-related simulation activity prior to the rollout and first hover flights of the XV-15. The mathematical model continued to be used for advanced tilt-rotor applications. Investigations of control, guidance, and display concepts[12] were conducted, as well as military applications and missions with advanced control configurations.

After the initial hover tests, the XV-15 was tested extensively in the Ames 40- by 80-Foot Wind Tunnel in 1978. These tests were preceded by off-line simulation of aircraft failures predicted to



AXIS	DISPL.	VELOCITY	ACCEL.
ROLL	$\pm 35^\circ$	1.3 rad/sec	10 rad/sec^2
PITCH	$\pm 35^\circ$	1.7 rad/sec	4.5 rad/sec^2
YAW	$\pm 35^\circ$	3.0 rad/sec	3.0 rad/sec^2
VERTICAL	$\pm$9 ft	7.5 ft/sec	8.8 ft/sec^2
LONG.	$\pm$9 ft	9.0 ft/sec	7.5 ft/sec^2
LATERAL	$\pm$9 ft	8.0 ft/sec	9.2 ft/sec^2

Fig. 12 Six-Degree-of-Freedom Motion Simulator.

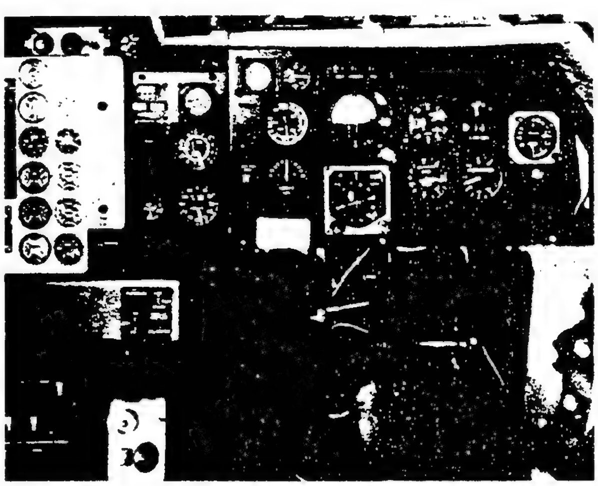


Fig. 13 XV-15 simulator instrument panel.

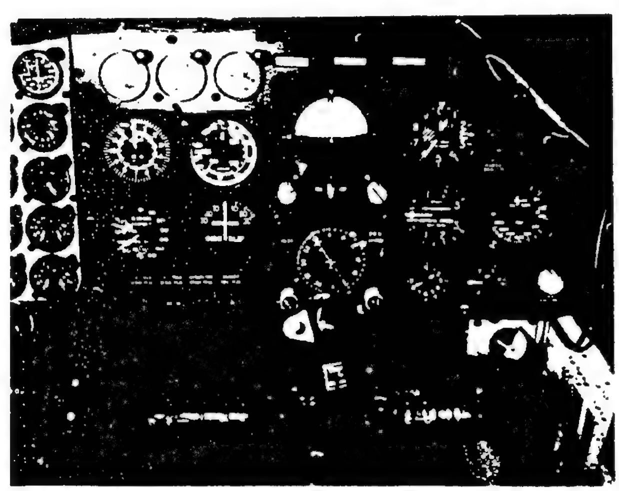


Fig. 14 XV-15 aircraft instrument panel.

• SIMULATION OF CONTRACTOR PROPOSALS	MARCH 1973
• LIMITED DESIGN EVALUATION	OCTOBER 1973
• SIMULATION OF SELECTED CONFIGURATION	DECEMBER 1973
• CONTROL SYSTEM AND HANDLING QUALITIES	JULY 1974
• OPERATIONAL AND BOUNDARY CONDITIONS	OCTOBER 1975
• MILITARY MISSIONS AND PILOT FAMILIARIZATION	MARCH 1980
• SCAS AND GOVERNOR MODIFICATIONS	OCTOBER 1980
• SCAS AND GOVERNOR MODIFICATIONS	MARCH 1981
• UNTESTED MODIFICATIONS AND CONFIGURATIONS	OCTOBER 1981

Fig. 15 Aircraft simulation chronology.

be critical during wind tunnel testing. This was done to identify potentially dangerous conditions and to develop recovery procedures. Additional moving-base simulations were conducted at Ames Research Center after the start of the contractor flight test program in April 1979. The first of these,[13] conducted in early 1980, had pilot familiarization as a primary objective along with limited evaluation of military missions. The next period, in the fall of 1980, was devoted primarily to control-system modification evaluations. It was conducted on the newly activated Vertical Motion Simulator at Ames while one XV-15 was being flight tested at the Dryden Flight Research Center, Edwards AFB, California. SCAS and governor modifications were evaluated and later tested in the aircraft. The following simulation, early in 1981, also involved SCAS and governor refinements. Finally, the most recent simulation activity at Ames was run on the FSAA in the fall of 1981 while both XV-15 aircraft were on flight-test status at Ames. In addition to future modifications and configurations, some simulation validation was accomplished.

An additional nonpiloted use of the simulation was the development of a parameter identification algorithm for use in stability and control flight testing.[13] The aircraft stability derivatives and response-time histories for various flight conditions were developed on the simulator. The time histories were then processed to obtain the derivatives via the parameter identification algorithm. The results are encouraging, and it is intended that the procedure will be used during the government flight-test program.

Accomplishments

During 9 years of XV-15 simulation, the primary program objectives were met. After the development of the detailed mathematical model, a valuable research tool was available to the design engineers and pilots involved in the aircraft development. Before flight of the aircraft, detailed design studies and analyses on the simulator resulted in major improvements to the XV-15 configuration and control system. Piloted evaluations permitted the optimization of control-system gains, the early investigation of failure modes, and development of cockpit procedures. Proposed design changes were evaluated and either incorporated in the XV-15 design, modified, or discarded, based on simulation results. The many hours of piloted operation of the simulator provided valuable training before flying this unconventional aircraft from one mode to the other. The intermediate, or tilt, modes were also investigated thoroughly. A major accomplishment of this extensive simulation activity was that there were no significant surprises to the pilots in flight, and that they were comfortable with the aircraft. The similarities of the simulation to actual flight, commented upon from the beginning, enhanced safety during the flight test program. In most cases, simulation limitations (to be discussed) made the aircraft easier to fly than the simulator.

As the test program progressed, the simulation model was updated to reflect flight-test data. Control-systems refinements were evaluated on the simulator before they were incorporated into the XV-15 design. These refinements, primarily to the rpm governor and SCAS, improved the response and handling qualities of the aircraft. Flight-test anomalies, real or predicted, were investigated, and in many cases resolved through the use of the simulation model.

In addition to the simulation activities directly related to flight test and configuration development, limited investigations were made of the XV-15's potential for military missions.

Problem Areas

A consistent problem with the XV-15 piloted simulation evaluations was height control in hovering flight. Initially, the problem was severe and caused vertical pilot-induced oscillations (PIO). This complicated vertical landing tasks, and, at times, the simulated aircraft could not be successfully landed. Part of the problem was identified as visual system time-constant errors and motion system washouts; although improvements were made, the problem was not completely resolved. Engine and power-lever (collective) responses were then improved by reducing the engine time-constant and providing some lead in vertical response to power-lever inputs. Considerable improvement in height control resulted. This PIO tendency is normally not encountered by the pilots in the actual aircraft; however it is identifiable on time history data. In hovering flight, most of the power-lever activity occurs within a foot or two of the ground because of downwash perturbations.

An apparent low roll damping caused many simulator pilots to induce low-frequency (about .5 Hz), low-magnitude roll oscillations in hovering flight. This tendency has been seen only to a slight degree in the aircraft. A roll SCAS limit cycle can be observed on strip-chart recorders during flight; however, most pilots are not aware of the oscillation. On the simulator it was common, and the PIO was distracting. A detailed evaluation of the roll dissimilarities between the aircraft and simulator was performed and is discussed in the section on fidelity.

Airspeed limits were imposed on XV-15 FSAA simulator operations because of numerical instabilities or computer cycle time effects. Generally, the simulator airspeed limit occurred at 230-240 KIAS and was manifested by the start of a low-magnitude, moderate-frequency pitch oscillation. This could be avoided by operating with the pitch SCAS off. In fixed base operation, it could not be seen by the pilot, but it was still occurring. These limits will affect higher speed XV-15 simulation investigations until cycle times are decreased. To date, the XV-15 has achieved 225 KIAS or 235 KCAS in level flight; the dive-speed envelope has not been investigated.

Limitations

As with any single-monitor television display, the field of view (FOV) available to the pilot was limited. For the FSAA, this field was 47° laterally by 37° vertically. The FOV from the pilot's seat (right side of cockpit) is shown in Fig. 16 along with that of the simulator. The limitations are obvious. In an attempt to improve the FOV over the nose, the viewpoint was biased 4° down. Some pilots perceived this as a slight nose-down attitude and corrected it with small, aft stick input. This caused a tendency to inadvertently start low-velocity, aft translations in hover.

The lack of all peripheral cues prevented some military missions from being evaluated. Shipboard operation was an example of this limitation. A straight-in approach to the hangar deck on the stern of a Spruance-class destroyer (DD963) could be made; however, 45° or sliding approaches to an LHA were not possible. Once on the deck of the destroyer, the hangar door filled the entire FOV, and attitude control was very difficult, especially in hovering flight with the deck motion for various sea states. The field of view was not as significant a problem when operating on an LHA, but deck-motion problems were similar. This is primarily a software problem in establishing aircraft contact with a moving deck.

The largest visual system terrain board used provides a flyable length of 13.2 km (8.2 miles) and a width of 2.7 km (1.7 miles). When pilots exceed these limits, they encounter a simulated cloud bank, and must go on instruments. This occasionally caused orientation problems, particularly during high-speed operations; however, the pilots generally adapted fairly quickly to this limitation. For extended cruise flight or evaluations without terrain board limitations, the camera could be placed in a "tub" which provided a 360° scene above the clouds, with distant clouds and sky for attitude reference. The loss of visual translation cues in this environment was not as significant to the pilot.

Future Applications

To date, only limited evaluations of advanced tilt-rotor applications,[12] other than those related to the project, have been conducted at Ames Research

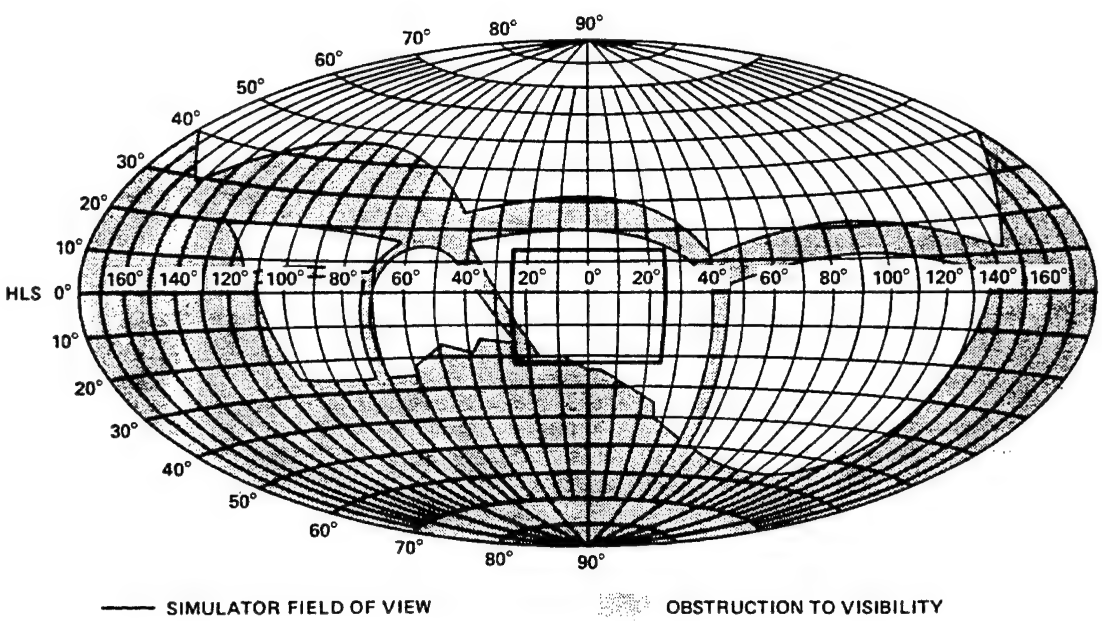


Fig. 16 XV-15 pilot seat field of view.

Center using the XV-15 simulation model. However, the military services are interested in the tilt-rotor concept for application to military missions, based on the demonstrated ability to perform the mission of a helicopter and that of a high-speed, turboprop airplane. The versatility of the concept is enhanced by its low noise signature, rapid acceleration/deceleration, and fuel efficiency.

Service demonstrations of the XV-15 are scheduled this year. These include the concept's evaluation for the Army's Special Electronic Mission Aircraft (SEMA), operations in a shipboard environment for the U.S. Marines/U.S. Navy, and operation in the nap-of-the-earth (NOE) environment. Some preliminary evaluations of these missions have been performed on the simulator. The simulation model also has the capability to permit investigations of growth versions of tilt-rotor configurations which meet military service requirements of the future. Scaled-up tilt rotors of the 35,000-lb class are being considered. In addition to military versions, the application of tilt-rotor technology to civil missions has been studied. Simulation offers an early look at certification criteria, both VFR and IFR, for this unique concept.

Additional areas where this existing simulation capability will be of significant value are in advanced control-system developmental work. These include sophisticated control-law formulations for alleviation of structural loads problems in maneuvers (rotor flapping controller), and in development of fly-by-wire/optics systems.

Simulation Fidelity

An assessment of simulation fidelity necessarily remains subjective from the pilot's viewpoint, although specific recommendations for assessment in terms of objective measures are beginning to appear.[14-17] Regardless of assessment technique, any specific determination of fidelity is tempered by the purpose of the simulation and the tasks to be performed. Good fidelity is assured if the simulation-generated cues cause the simulator task to specifically relate to the real-world task or if that which the pilot experiences and learns in the simulator adequately prepares him for the actual aircraft experience. Sinacori[14] defines fidelity in two ways: engineering fidelity, meaning the measured closeness to the real world; and perceptual fidelity, meaning the perceived closeness to the real world. Good perceptual fidelity is obtained when the pilot gets out of the simulator saying, "That is the airplane." If the simulation engineering staff can fully corroborate or rationalize the basis for the pilot either making or not making this statement, then both fidelity categories are defined. The following discussions present the major fidelity issues encountered during the various XV-15 simulations, and the steps taken to improve the perceptual fidelity, without compromising the engineering fidelity.

Digital Cycle-Time Effects

In any digital simulation program, a prime item affecting the simulation fidelity is the cycle time--the time increment from digital computer read-in to system response as seen by the pilot. For example, if the pilot inputs a control displacement, the increment enters the digital computer at the first read-in point, the data are processed during the time interval, and the response is returned to the pilot an average of 1.5 cycles after his inputs. This shows up as a discrete time delay, essentially giving the pilot an apparent adverse phase shift, with no gain change. If the pilot is providing a control input at 0.5 Hz, the phase lag increment is -18° for a 67-msec cycle time. This is a simplistic view of this effect. The significant point is that if an aircraft system is marginal on response, such that a pilot-induced oscillation (PIO) tendency exists, the cycle-time delay can make it critical. Also, if cycle times become large, there is the possibility of the pilot being aware of the digital updates through a "ratchet"-type effect in perceived visual system responses. Based on these problems, it is desirable to maintain the cycle time as low as possible, preferably less than 40 msec.

Because of the size and complexity of the XV-15 mathematical model, the cycle times have always been in excess of 50 msec, and during recent experiments, as high as 70 msec. This long cycle-time contributed to three specifically identified simulation problems: a roll-control PIO problem at low airspeeds in helicopter-mode flight; a vertical-mode PIO tendency at low airspeeds; and a high-airspeed numerical instability in the pitch axis, with the stability and control augmentation system (SCAS) engaged. It also required a compromise in the landing gear modeling.

Roll PIO Problems. The roll PIO problem was most severe with the most recent simulation efforts, when the cycle-time approached 70 msec. This was due to increased sophistication of the simulation to include ship dynamics for carrier compatibility evaluations, and this was also the first time measured aircraft control hysteresis was used extensively during routine evaluations. The problem was further aggravated by a change made in the visual system drive parameters which caused an unexplained additional lag, not detected during the setup period, and also, not present in prior simulations. During this simulation period, the aircraft was also in flight test, enabling specific test data to be obtained to investigate the discrepancy between flight and simulator characteristics. These data are presented in Fig. 17 as the simple roll degree-of-freedom frequency response characteristics in hover.

The first step in developing the data shown in Fig. 17 was to calculate the rigid airframe-controls response characteristics, using perturbation derivatives obtained from the simulation. This was considered valid, since flight checks of aircraft control sensitivity (roll rate per inch control) showed good agreement with simulation results. The aircraft response-time constants were not determined. The aircraft oscillatory response data were then obtained at frequencies of 4.5 and 6.6 rad/sec, and compared with the simulator response (without hysteresis); the gross discrepancy in both the aircraft and simulator phase relative to the calculated rigid airframe phase was then found. The aircraft discrepancy was resolved by incorporating the known control flexibility,* which had been documented

*Churchill, Gary B., Clement, Warren F., and Craig, Samuel J., "XV-15 Tilt Rotor Aircraft Control Systems Status Report," Tilt Rotor Research Aircraft Project Office, NASA, ARC, Moffett Field, Calif.

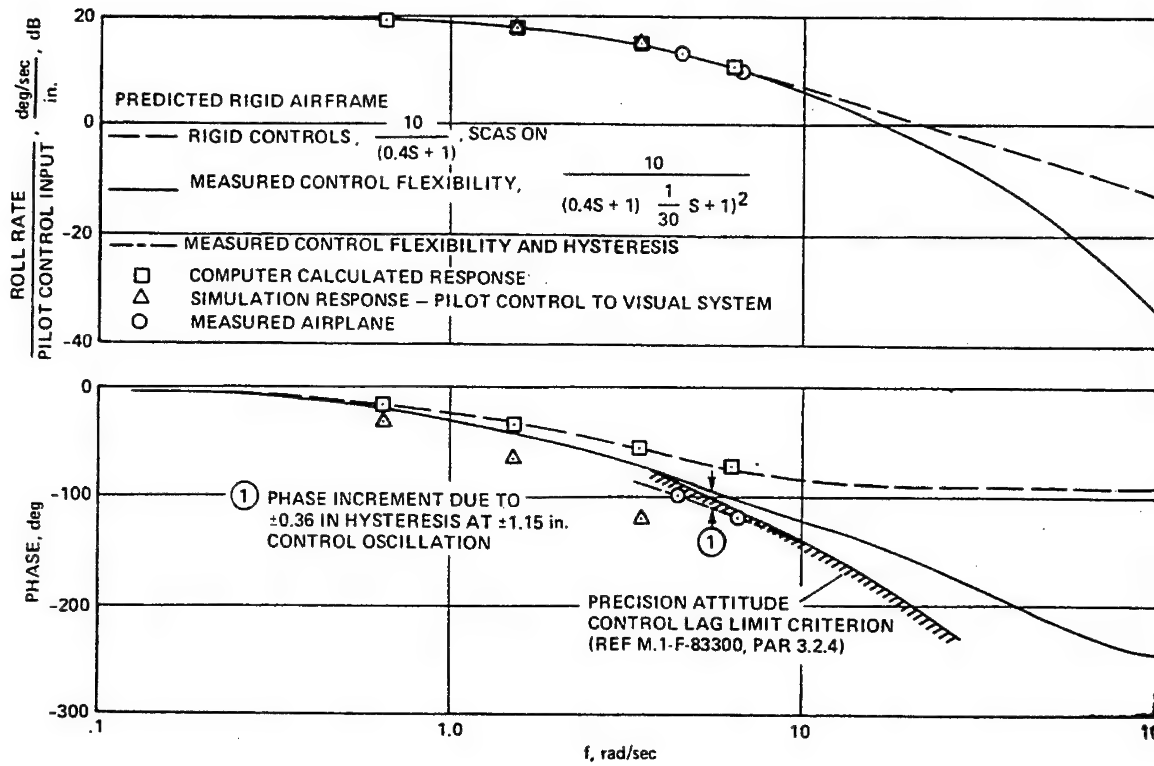


Fig. 17 XV-15 hover roll response: aircraft versus simulation, attitude retention off.

during the aircraft control-system integrated systems tests, and adjusting the phase for the effects of control hysteresis.[18] The gain increment predicted by Ref. 18 does not show in the aircraft response because of a unique SCAS design. This completely rationalized the aircraft discrepancy and, with the inclusion of the attitude control lag-limit criterion,[19] substantiated the aircraft PIO tendency. The basis for the simulator PIO characteristics was fully substantiated by the visual lag; however, the anticipated phase lag increment was 18° at 3 rad, not 63°, as measured.

The visual system roll axis normally has a 0.22-sec lead installed, which compensates for a smoothing filter installed to prevent the "ratchet" effect owing to cycle-time from being apparent to the pilot. This lead was increased to 0.45 sec; the effect of the lead is presented in Fig. 18. These data were obtained by driving the lateral stick trim position, with the attitude-retention SCAS mode engaged. The stick gradient was increased to attempt to prevent the stick from "breaking out" of trim, because of the motion, since this disengages attitude retention. This worked for the two low-frequency points, but not at frequencies above 2 rad/sec, and caused the amplitude response to be higher than predicted in this region. The effect of the 0.23-sec lead was to increase the response by 3 dB at 3 rad, and to bring the phase into very close agreement with predicted aircraft characteristics. (These shaping functions for altering the visual response characteristics are discussed in detail in Ref. 5.) For this configuration, then, the response closely approximated the aircraft with control flexibility, but with no hysteresis. Reference 20 provides an excellent technical analysis of the importance of visual display lag effects and compensation. During these tests, the motion-system response was also evaluated; it showed reasonable correlation with the aircraft. The previously established phase for 0.22-sec lead is presented for comparison.

On the day following the implementation of this "fix," a pilot encountered the roll PIO in the aircraft, while on final approach. His comment during the postflight debriefing was, "You've fixed the simulation, now fix the ..... airplane!" This work is in progress.

These data are unique, in that correlation data of this depth are rarely available. However, the requirement for perceptual fidelity to be corroborated by engineering fidelity evaluations is vividly demonstrated.

Vertical PIO Problem. The vertical-mode PIO problem was quite similar to the roll problem. The present aircraft thrust/power management system creates a slight PIO tendency on approach, which can be seen in flight data time histories. Pilots have excited this on occasion, but not for more than 3 to 4 cycles. As in the roll problem, when hysteresis was introduced in the simulation, all pilots had PIO problems. Even without the hysteresis, the simulator was always more critical. Investigation of the mathematical model showed the engine response-time constant to be high by a factor of 3 (1.8 sec instead of 0.6), based on engine-test-stand data provided by Lycoming. One additional problem was found by checking visual system vertical-drive errors, and finding a drive-system lag which was unrelated to cycle time. This combined with the

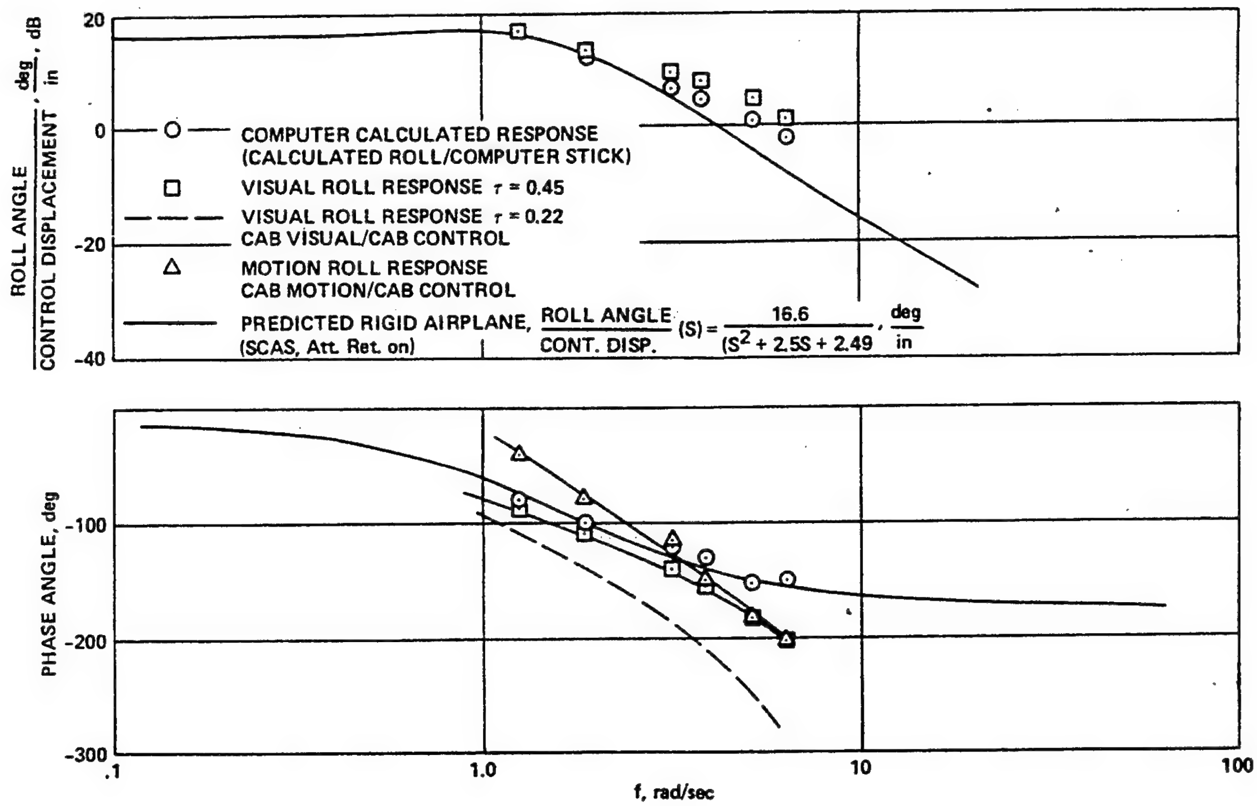


Fig. 18 XV-15 simulator roll response.

digital cycle-time delay to give a total system delay of about 0.2 sec at about 3 rad/sec. Resolving the vertical response problem then required elimination of the hysteresis and adding lead compensation in the visual vertical drive to eliminate the drive error. System design changes to alleviate the actual aircraft PIO tendency are presently being evaluated, and will be incorporated in March 1982. This problem was less severe on the VMS than on the FSAA, indicating that it may be partially caused by vertical motion cueing. Sufficient specific fidelity evaluations to rationalize this have not been obtained.

Numerical Instability. The numerical instability at high speeds, SCAS on, results from a numerical instability in the pitch SCAS trasnfer function integration algorithm caused by cycle-time delays. Several fixes have been attempted; all were minimally effective. The net effect is a large-amplitude, high-frequency, pitch limit-cycle that occurs at about 240 knots at cycle times of about 60 msec, and at 190 knots at a cycle time of 70 msec. The divergence airspeed appears to be approximately an inverse function of the cycle-time. Since the primary use of the simulation has been at lower airspeeds, further resolution of this problem has not been attempted.

Landing Gear. The final element of the simulation significantly affected by digital cycle-times is the landing gear modeling. Reasonable simulation cycle-times for landing gear modeling are of the order of 2 to 4 msec because of the extremely high rate of change of landing gear loads during touchdown. The XV-15 cycle-time requirements therefore precluded using an accurate model; however, a simplified model was developed which reasonably represented the touchdown and roll-out characteristics. This modeling is adequate for gross evaluations of taxi and ground handling. The modeling of the gear is invalid at simulated power settings of less than 20% where numerical instabilities occur.

Simulator Hardware Effects

The simulation hardware affecting the dynamics of simulation fidelity are the flight controls, the motion and associated washout systems, and the visual systems. These systems critically affect the fidelity in all phases of operation, occasionally in subtle, unanticipated ways. At the onset of the simulation program, it was determined that specific, definitive criteria and methods for evaluating simulation fidelity, as affected by these systems, were lacking. Systems Technology, Inc. was, therefore, asked to provide these[21] under the ongoing support services contract for the XV-15.

The procedures developed by STI defined the performance data requirements and criteria for initial evaluations, as well as suggested periodic checks to be made against possible degradations owing to "wear and tear." A summary of the significant checks and evaluation criteria is presented in Fig. 19. The visual system performance checks were added by the tilt-rotor Project Office in 1981, following the previously discussed roll PIO problems. With the exception of the static alignment procedure for visual system setup, all fidelity check procedures have been automated to facilitate

SYSTEM	CHECK	PROCEDURE	NORMAL FREQUENCY
VISUAL	1. STATIC ALIGNMENT	1. TEMPLATE ALIGNMENT	DAILY
	2. LINEAR CALIBRATION	2. MAINTENANCE	WEEKLY
	3. DYNAMIC RESPONSE	3. SAFE*	WEEKLY
	4. PERFORMANCE	4. STRIP CHART RECORDING OF POSITION ERRORS DURING NORMAL OPERATIONS	DAILY
MOTION	1. DYNAMIC RESPONSE WASHOUT PROGRAM IN/OUT	1. SAFE*	WEEKLY
	2. THRESHOLD/SMOOTHNESS	2. AUTOMATED MOTION CHECK	DAILY
CONTROL LOADERS	1. GRADIENT, BREAKOUT FUNCTION	1. X-Y PLOTS OF FORCE vs DISPLACEMENT	SETUP
	2. DYNAMIC RESPONSE	2. SAFE*	SETUP

*SIX AXIS FREQUENCY EVALUATION

Fig. 19 Simulation hardware fidelity evaluations.

their use in the event such use is warranted by suspected malfunctions.

Visual System. The capability to perform fidelity checks quickly and easily is of particular importance with the visual systems. These may be used as much as 16 hr per day on a variety of simulations, with only weekly maintenance, unless specific faults are identified. The static alignment procedure is performed during set-up at the beginning of a shift. This is normally sufficient, but if the simulated aircraft requires a low pilot-eye height in the runway, the alignment must be repeated several times during the day (because of temperature effects on the structure supporting the terrain boards and the camera gantry). The linear calibrations and the dynamic response of the system using the SAFE* procedure are normally not variant, and the weekly checks during maintenance should be sufficient.

The overall performance checks, added in September 1981, were found to be the most important during operations. These were done using the full-up simulation, and performing relatively severe low-altitude, low-speed maneuvers, which included lateral and longitudinal quick stops, jump takeoffs, and hard landings. The time-history plots of the visual-system errors gave an immediate presentation of any system problems, such as degraded servo performance, or hysteresis and threshold problems. It was found that this procedure was at times more effective in locating system malfunctions than the normal maintenance procedures.

Motion System. In general, the motion system performances on both the FSAA and the VMS were consistent during simulation periods. The daily motion checks adequately verified overall performance, and the weekly SAFE runs provided complete software and computer equipment verifications. The only significant deficiency is the lack of a capability of evaluating the motion drive and washout logic systems and making direct comparisons with calculated aircraft responses. As with most simulator motion systems, the determination of washout characteristics is somewhat of a "black art," and adequate cab instrumentation (linear and angular accelerometers or rate gyros) have not been available for specific determination of cab-to-aircraft response transfer function. The motion-drive logic parameters are set up by a "simulation" pilot operating the system before it is given to "real" pilots. This occasionally requires iterations, especially if the simulation is of a real aircraft, such as the XV-15.

Control Loaders. McFadden control loaders were provided for the control sticks and pedals, and they were found to be quite reliable in all simulations. The data for force versus displacement and frequency responses were spot checked periodically and did not change.

Flight-Test Data Correlation

The final test of both engineering and perceptual fidelity comes with comparison of simulation and flight-test results. To date, the scope of the XV-15 flight-test program has included envelope expansion and aeroelastic stability testing. This has provided significant amounts of performance and trim data. Handling qualities have been evaluated only qualitatively; however, some dynamics data have been obtained for evaluation of specific aircraft anomalies.

Performance. Level-flight predicted and measured performance data are presented in Fig. 20. The only change in the simulation program to generate the predicted data was to increase the flat plate drag from 7 to 9 ft^2. This increment was based on the XV-15 wind-tunnel tests performed in 1978.

*SAFE—Six-Axis Frequency Evaluation—is a program originally designed to measure the frequency response of the motion base. It has also been adapted to use on the visual systems and McFadden loader systems.

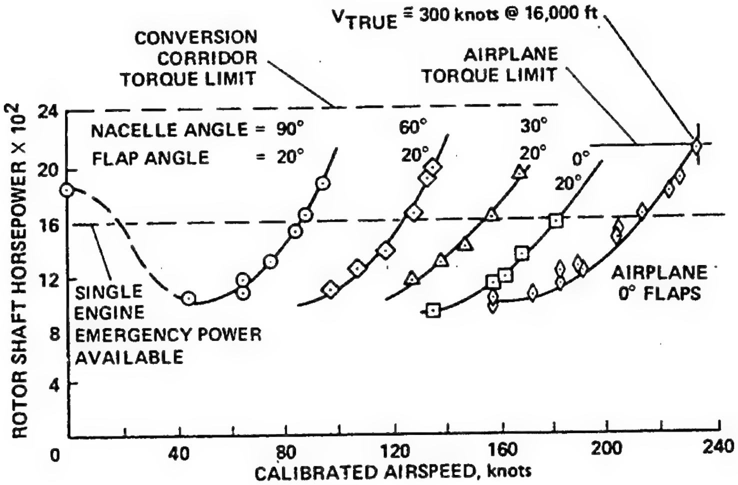


Fig. 20 XV-15 Level-flight performance.

Static Trim. The static longitudinal trim curves are presented in Fig. 21 as functions of airspeed and nacelle incidence angle, i_N. Correlation is generally good, with the deviation between prediction and test increasing as the aircraft is converted from the helicopter to airplane mode. This is attributable to errors in modeling of the downwash at the tail. The simulation model is based on small-scale wind-tunnel data, and two minor discrepancies exist: one is caused by flap effects, the other by wind-tunnel wall effects. The downwash discrepancy between prediction and flight data at 160 knots, with flaps retracted, is approximately 1°.

Dynamics. The real essence of simulation fidelity is in obtaining good correlation on system dynamics: pilot responses, disturbance responses, and stability problems. The specific handling-qualities issues have not yet been addressed in the flight-test program, so comparative data are generally not available. Qualitative evaluations of short period, dutch roll, and maneuver characteristics have not indicated significant disparities between the aircraft and the simulation. Hover control responses in pitch, roll, and yaw with SCAS modifications were evaluated, and control sensitivities in flight were very close to design values established on the simulator. The roll axis dynamic response data obtained for the fidelity checks also bear this out. There were, however, two additional simulation fidelity checkpoints flown where specific comparative data were obtained, and one instance of flight instability predicted on the simulator.

The flight-stability problem, caused by the rpm governor, occurs at high sink rate (2,500 ft/min) and at about 70 knots airspeed. It is characterized by large-amplitude rotor-speed, pitch-attitude, and sink-rate oscillations. When first encountered on the simulator (1975), the pilots would consistently either crash or abort. The recovery procedure defined was simply to increase power. The instability was first encountered on the aircraft during the first high-sink-rate approaches in 1979. Governor time-history data from this flight and from the simulation are presented in Fig. 22. The decay of the oscillation occurs in both cases after power application. This governor instability problem has since been fully resolved, using a simulation defined modification to the governor. It was not resolved when discovered on the simulation, because the contractor did not believe it was "real"; however, the Project Office thought it was real, and a safe, effective recovery mode was defined. Flight safety was the only basis under the terms of the contract on which the Project Office could force design changes.

The two additional flight checks for fidelity data were flown because the pilots believed that the simulator trim change with flaps and trim change with power in airplane mode were excessive. This was during a period when the simulation was operating simultaneously with XV-15 flight-test operations at Ames Research Center, and the flight-test plan included airplane-mode operations. These data, presented in Figs. 23 and 24, show good correlation between the aircraft and simulator. In these instances the engineering fidelity is shown to be quite good; before flight checks, however, the perceptual fidelity was regarded as poor. The reason for this is not fully understood; however, it does point out the value of flying specific manuevers on both the simulator and aircraft for fidelity comparisons. A rationale may be that the limited acceleration capability in the simulator biases the perceptual fidelity. The net result is that this contributes to the tendency of the pilots to treat the actual aircraft much more tenderly than they do the simulator.

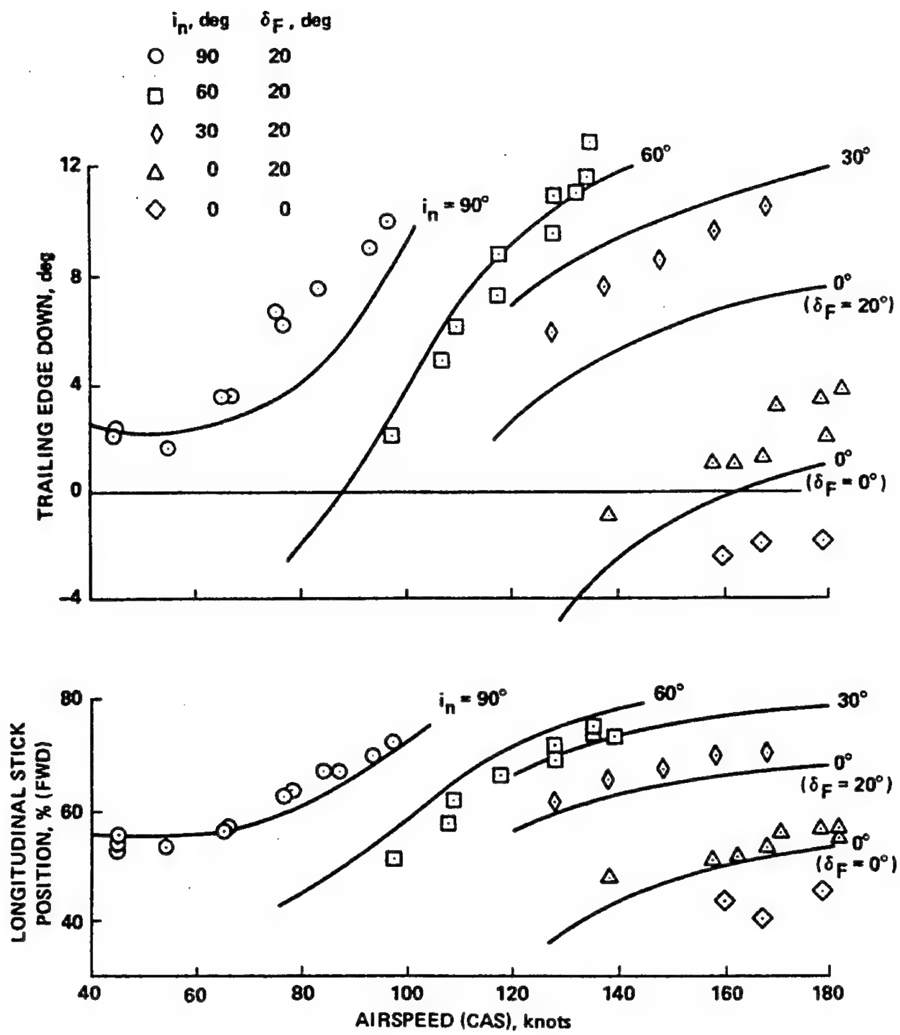


Fig. 21 XV-15 Longitudinal control versus airspeed.

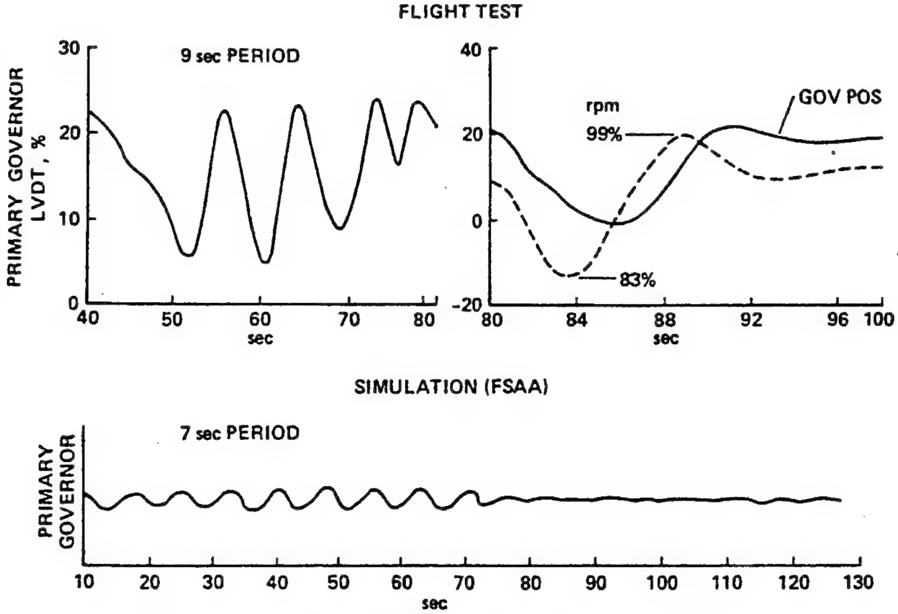


Fig. 22 Governor instability-time history comparisons.

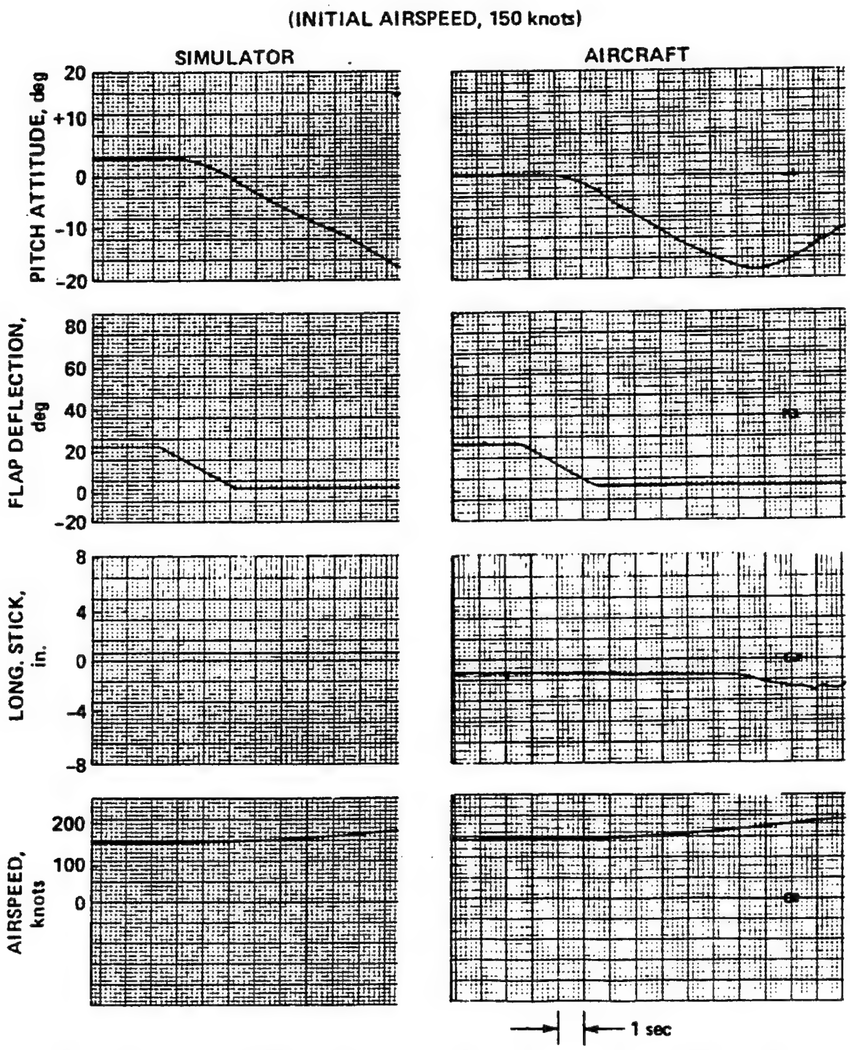


Fig. 23 Simulator versus aircraft: trim change with flap retraction (initial airspeed 150 knots).

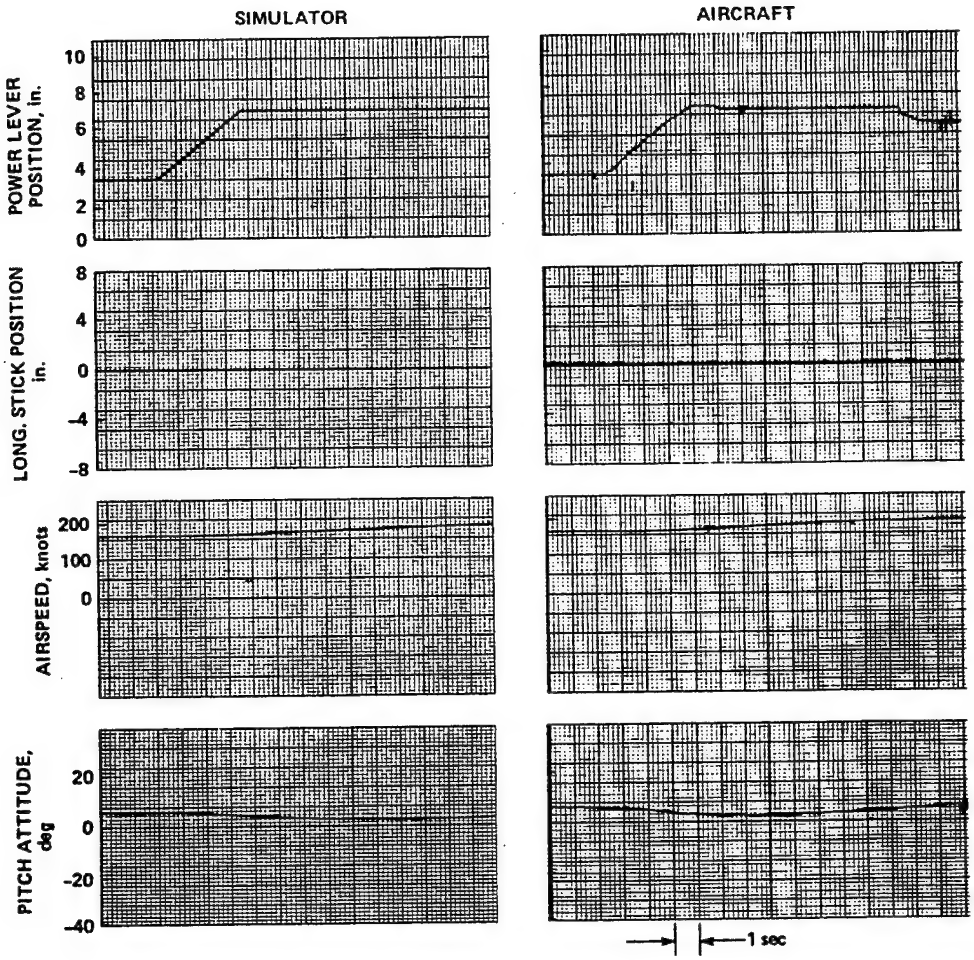


Fig. 24 Simulator versus aircraft: trim change with power pull (initial airspeed 163 knots).

Conclusions

The following conclusions derive from the XV-15 Tilt Rotor Research Aircraft simulations studies:

1) Simulation has been a powerful tool in procurement, design, development, and flight test of the XV-15 tilt-rotor aircraft.

2) A requirement for simulation during proposal evaluations provides major benefits to the procuring agency.

3) Perceptual fidelity evaluations of simulation are invalid without engineering corroborations.

4) Engineering fidelity evaluations require full equipment dynamic response evaluations, as well as evaluations of the mathematical model.

5) Use of simulation for developing specification or certification criteria is invalid without first evaluating the simulation fidelity.

6) Fidelity evaluation procedures and criteria are the most significant deficiencies in this "art."

7) As a result of simulation fidelity evaluations, a potentially critical aircraft roll PIO problem was identified.

All of this simulation effort—although it accomplished specific objectives in XV-15 design, evaluation, and pilot training—had another significant effect on the program: this was the confidence of the pilots and engineers in the design and handling qualities of the aircraft. The XV-15 continues to safely demonstrate tilt-rotor technology for military and civil applications.

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F/A-18 MISSION COMPUTER SOFTWARE TESTING USING THE NAVAL AIR TEST CENTER TACTICAL AVIONICS AND SOFTWARE TEST AND EVALUATION FACILITY

Mr. R. Smullen & Mr. R. Newberry
Naval Air Test Center
Patuxent River, Maryland

Abstract

The current generation of United States strike aircraft has incorporated a level of technical sophistication which is orders of magnitude greater than previous generations. Implied in this increased sophistication is an increase in system complexity which taxes the Department of Defense's capability to adequately test new aircraft products. Combine this with reductions in funding and compressed schedules and you have the scenario that faced the Naval Air Test Center (NAVAIRTESTCEN) in 1977 when the F/A-18 arrived for testing. It was obvious that an alternative to the standard practices of weapon system test and evaluation had to be developed. The Tactical Avionics and Software Test and Evaluation Facility (TASTEF) was NAVAIRTESTCEN's answer to the problem. Developed to fill the gap between the contractor's tests and the Navy's limited flight test efforts, the laboratory was designed around the MIL-STD-1553 bus architecture of the F/A-18. A federation of commercial minicomputers, special display processors, F/A-18 mission computers, and a variety of special purpose interfaces comprised the hardware of the laboratory. Models of the aircraft avionics system, a multiprocessor executive, and special purpose drivers were included in the software. Together they provided the capability to stimulate the aircraft mission computers as would occur in a flight environment. Algorithm and module tests could then be conducted, in the laboratory, throughout the envelope of the F/A-18 airplane. Critical points in the envelope or specific deficiencies would be identified for flight test concentration or verification. The TASTEF is currently involved in the F/A-18 test efforts. Hardware and software for the AV-8B are under development, with support for flight test planned for CY-1982.

Introduction

In early 1976, NAVAIRTESTCEN began to make plans for its role in the test and evaluation of the F/A-18 airplane. As the name indicates, this was not just a fighter or attack airplane but an attempt to combine both tactical capabilities in the same airframe. Initial estimates of the number of flights it would take to adequately test the airplane were staggering. To give you an idea of the number required, consider the following. Statistical analysis has shown that a minimum sample size of 18 is required to adequately quantify a weapon/weapon system mode combination (reference 1). This means that 18 weapons should be fired/released in each combination of weapon release mode (5), sensor mode (10), and weapon delivery profile (conservatively set at 8). The F/A-18 airplane carries an arsenal of 45 different weapons. Some simple arithmatic shows that a total of 324,000 weapons must be fired/dropped to assure adequate system performance. An average flight for the F/A-18 on the Chesapeake Test Range consists of 12 runs. This means that a total of 27,000 flights would be necessary to thoroughly exercise the system. If we assume an optimistic success ratio of 70% and a sortie rate of five per day (extremely optimistic), we would be flying nonstop for the next 21.14 years. This does not include the air-to-air (A/A) modes of the airplane.

Obviously, a need existed to change the groundrules that NAVAIRTESTCEN had been operating under to determine weapon system performance. A new tool had to be developed to compliment the traditional flight test. The TASTEF was NAVAIRTESTCEN's response to this requirement. Developed not to take the place of flight testing, but as an economical alternative, the concept was to examine the full envelope of a weapon system performance capability through carefully controlled laboratory tests. These tests would identify critical areas in the performance envelope which would then be closely scrutinized in the more expensive flight tests. Anomalies and discrepancies identified during flight tests would be verified in the laboratory and studied in-depth in that controlled environment. Cross-checking of flights and laboratory results would increase the fidelity of TASTEF software models and increase confidence in laboratory results.

Architecture

Figure 1 shows the hardware architecture of the TASTEF. At the center of the laboratory are two AN/AYK-14 mission computers. These units are identical to those in the F/A-18 and run the F/A-18 Operational Flight Program (OFP) during tests. Clustered around the mission computers is a federation of commercial minicomputers which run the simulation software. Two special purpose display processors provide the user with F/A-18 displays. The minicomputers communicate with the mission computers via a MIL-STD-1553 multiplex bus. This is a 1 MHz serial bus identical to that in the airplane. The final element is an interrupt structure which provides for laboratory synchronization.

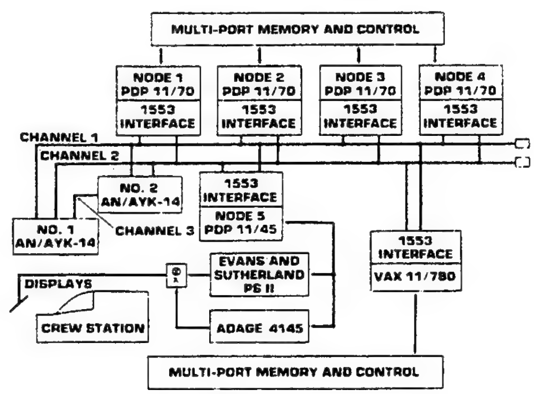

Figure 1 TASTEF Hardware Architecture

F/A-18 Testing

The TASTEF runs in three distinct modes of operation. In the "simulation mode," the laboratory appears to the user as an F/A-18 with dynamic flight characteristics controlled by an active stick and throttle. This mode is used by test pilots and engineers to prefly tests to ensure that all moding, weapon select, etc., has been properly

defined for the upcoming flight. This mode is also used to verify anomalies, discrepancies, and actions noted by pilots during flight testing. The "playback" mode of the TASTEF is not used in the F/A-18 testing and, consequently, will not be discussed in this paper. A third mode of operation is the "static mode." In this mode, engineering evaluations of mission computer algorithms can be very precisely carried out. Four specific static tests were identified which could significantly reduce the number of flights required for F/A-18 performance evaluation.

Ballistics Evaluation

An important capability of any weapon release system is its ability to accurately predict the trajectory of the weapon. While Navy laboratories provide the contractor with the characteristics of the weapon, the algorithm which the contractor uses to derive a predicted impact point is usually left to him. The ballistics test was a comparison of the F/A-18 algorithm with a fourth order Rung & Kutta algorithm (reference 2), which was considered the "truth" model.

Air-to-Ground (A/G) Sensitivity Analysis

The A/G sensitivity analysis provides insight into the contractor's weapon delivery system implementation. By introducing perturbations or errors into the F/A-18 sensor models and analyzing the results of those perturbations on the weapon delivery calculations, the TASTEF can effectively determine the "sensitivity" of the weapon delivery algorithms to sensor errors.

Launch Acceptable Region (LAR) Evaluation

The LAR is the A/A equivalent of the ballistics algorithm. The LAR shows the maximum and minimum ranges for a successful launch of a missile under the current fighter/target geometry. The F/A-18 carries two different A/A missiles, the AIM-7F (Sparrow) and the AIM-9L (Sidewinder). The LAR evaluations for both missiles were conducted using high fidelity missile models (reference 3) for "truth" data.

LAR Sensitivity Analysis

The LAR sensitivity analysis will provide the same insight into the contractor's LAR algorithms as the A/G analysis did for weapon delivery. This analysis is not complete and will not be discussed in detail at this time.

Software

The software modules that comprise the TASTEF can be broken into three general categories: Sensor/Avionics, Environmental, and Special Purpose. The Sensor/Avionics models comprise the core of the TASTEF and are responsible for providing the laboratory's "personality." When the avionics models of the F/A-18 are loaded, the TASTEF appears to the user as an F/A-18. When the AV-8B models are loaded, it appears as an AV-8B, etc. Typical of this category are Radar, Communication System Controller, TACAN, Radar Altimeter, Air Data Computer, etc. The fidelity of the avionics models is dependent upon the need but, generally speaking, these models represent "perfect" sensors, in that they perform exactly as the specification requires.

With the exception of the airframe and engine models, the environmental models are independent of the aircraft being simulated. These models provide the "environment" necessary to make the avionics models think they are in a real airplane. Environmental data is passed between processes and processors by means of a multiport memory (figure 1). Typical environmental models include airframe, engine, earth, atmosphere, and target. Here again, the fidelity of an individual model is dependent upon the specific tests to be undertaken. In the case of environmental models, however, a lower fidelity can usually be accepted. For example, most weapon delivery systems would not respond differently in a ballistics analysis if an F/A-18's F404 engine was replaced by an F-4's J79 engine.

The final category of software modules is a catch-all for what remains. This represents the special purpose software to interface between the TASTEF computers and the user. A multiprocessor executive is the primary module in this category. The executive processes a configuration file (figure 2) to determine what software personality the user desires. From the information available in this file, the executive fetches the task images required and installs them in the appropriate processor(s). When all processors have been loaded, the executive informs the user and offers him a variety of options. At this point, he may RUN the simulation in real-time, STEP the simulation a single cycle, run in DEBUG mode, or STOP the simulation. A variety of other special prupose software is also used to interface the crewstation switches and lights to the computers, provide microcode emulations of the F/A-18 display processors, allow boot-loading of F/A-18 mission computers, etc. The special purpose software is very application dependent with the exception of the executive changes for each different aircraft simulation.

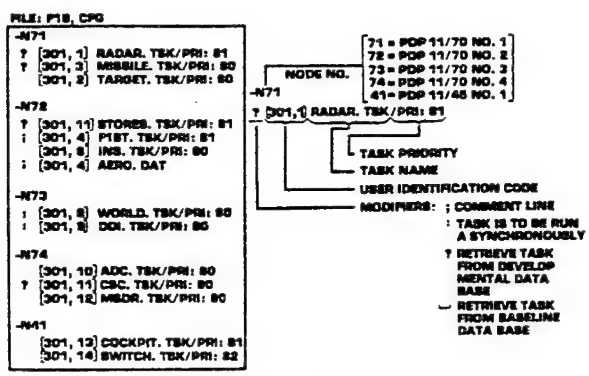

Figure 2 Typical TASTEF Configuration File

Test Drivers

In order to perform the ballistics and A/G sensitivity tests discussed previously, modifications were necessary to several of TASTEF's avionics and environmental software modules. The airframe model's root segment was modified to incorporate a series of nested DO LOOPs which would increment aircraft altitude, airspeed, pitch angle, and angle-of-attack. The DO LOOPs were table driven to provide starting, ending, and incremental values for the aircraft parameters. In addition, the aircraft's X and Y (grid) positions were set to zero. The combined effect of these modifications was an aircraft which appeared to be fixed in space in the state defined by the DO LOOP. This is a particularly powerful environment since, even though the mission computers think they are flying, the inputs to the weapon delivery equations are static and the resulting weapon delivery solution is constant. This is precisely the software configuration which was used for F/A-18 ballistics verification tests. The delivery envelope for a particular weapon was described to the TASTEF in the form of starting and

ending altitudes, airspeeds, pitch angles, and angles-of-attack. As the laboratory was stepped through each of these release conditions, the laboratory was "frozen" for 1 second to allow the mission computer's solution to settle. The results of that computation were stored on disk for later analysis and the laboratory was stepped to the next release condition. In this configuration, the TASTEF is capable of stepping at approximately one data point every second. In 12 seconds, the laboratory has produced data that would have taken an hour to collect in flight.

In order to perform the A/G sensitivity analysis, a further modification was necessary. The sensor models were modified to allow error insertion. The protocol was to provide the sensor model with an error value via the multiport memory. That error value was then either added or not added to the sensor's output depending upon the state of a flag, also located in multiport. The aircraft model's root segment was then modified to include an additional DO LOOP which alternatively set and cleared that flag. The result was a case with the error immediately followed by a case without the error. The difference in the weapon delivery computations between these two cases was the net effect of the induced sensor error. Once again the laboratory was exercised throughout a delivery envelope for a specific weapon. At each step in the test, the laboratory was "frozen" and data stored on disk for later analysis. A variety of sensor models were modified in this manner, enabling the analyst to observe the independent effect of a variety of potential sensor errors.

Instrumentation

The instrumentation requirements for the A/G testing were two-fold. First, we needed to snapshot the state of the airplane at each release condition. This was easy since this data was stored in a global common that all TASTEF processors had access to. The second part was to record certain internal mission computer parameters which were required for analysis purposes. To do this, advantage was taken of the "instrumentation module" which was installed in the F/A-18 mission computer software. This module was designed to aid the flight test engineers in their test and evaluation of the F/A-18 airplane. Briefly, this module could retrieve virtually any internal mission computer parameter and transmit it, via the 1553, bus to a special instrumentation system which appeared as a remote terminal on the bus. By queueing one of the TASTEF's remote terminals to appear as that same device, the TASTEF could also have access to the internal variables of the mission computer. A special software handler was written to access this and airplane state data and store it on disk for post-test analysis.

Data Analysis

Ballistics

Horizontal range bomb travel (Hr) and time of flight (Tf) values were computed by the F/A-18 mission computer over the entire release envelope for each weapon. For each release condition, Hr and Tf were computed using the truth model and compared to those computed by the F/A-18 mission computer. Differences constituted an F/A-18 ballistic mechanization error. The mechanization errors were grouped by weapon type and delivery condition for further examination to determine the accuracy of the mechanization relative to weapon type and/or delivery condition.

Mean, standard deviation, and root mean square were computed on the errors in each group of data. Examination of these statistics ascertained whether a bias existed and evaluated the repeatability of the errors. Additionally, the minimum and maximum errors were examined to obtain the extreme spread of the mechanization error. The statistics from each group of data were compared to the statistics from every other group. In this manner, a determination was made upon the accuracy of the F/A-18 mechanization relative to weapon type and/or type delivery condition. These results were also used in sensitivity studies of the overall F/A-18 weapon system.

The results from this analysis showed the F/A-18 ballistic mechanization accuracy to be independent of delivery condition, although dependent on weapon type. Deficiencies were written on the mechanization of specific weapon types and corrective action was initiated by the contractor. The significant fact here is that it is highly unlikely these deficiencies would have been discovered during the Board of Inspection and Survey (BIS) trials.

A/G Sensitivity Study

In any weapon delivery system evaluation, a correlation between weapon system sensor errors and weapon impact miss distance must be acquired. In analyzing a weapon delivery system, sensor errors are isolated and their effect on the weapon impact miss distance calculated. After all error sources are isolated and their effects upon miss distance examined, the miss distance can be described in terms of error source effects. The correlation between weapon impact miss distance and weapon system performance is then provided.

To prepare for the F/A-18 weapon system analysis, a sensitivity study was conducted to determine the effect upon system performance of individual sensor errors. This was done by introducing error in the F/A-18 sensor models and collecting the results of the input errors upon the weapon delivery calculations. The sensor errors and their effects were collected over the entire release envelope for a given weapon and grouped relative to sensor. In this manner, the accuracy of the F/A-18 weapon delivery calculations were thoroughly analyzed relative to specific sensor accuracy. This allowed a ranking of sensor or calculations (such as ballistic mechanization, etc.) effects, from those with the most significant effect on weapon delivery accuracy to those with the least effect.

Originally, the values for sensors errors in the perturbations were the values quoted in the performance specification for each sensor. As data were acquired during flight tests, actual sensor errors were computed using the test data. The sensitivity study was then updated using actual sensor errors in the pertubations providing a more realistic analysis.

Assuming individual error effects, derived from individual sensor errors, to be independent, the error effects were grouped together. This was done to examine the overall accuracy of the F/A-18 weapon system, given some form of sensor error would be present. A total or overall error effect was calculated by root sum squaring the standard deviations of the error effects derived from the sensitivities. Once the total error effect was calculated for the in-range (long and short) and cross-range (left and right) components, a predicted Circular Error Probable (CEP) was calculated. Since the sensitivities were derived for any type release condition or weapon type, a predicted CEP could be calculated for any release condition or weapon type.

As BIS test flights are flown, the actual weapon impact miss distances will be compared to the predicted CEP for that release condition and weapon type. This process will point out anomalies in the test data and increase confidence in the laboratory tests. As data are acquired in a given mode, statistical tests will be done comparing flight test data to the sensitivity data. Depending on the outcome of the statistical tests, a possible saving of test flights in any given mode may be possible. In this manner, a better utilization can be made of the allotted BIS flight tests.

Additionally, the sensor and sensor error data acquired during the BIS weapon delivery flight tests will be run through the sensitivity study. This process will describe each weapon impact acquired in terms of sensor errors, providing the correlation between weapon impact miss distances and weapon system sensor errors. Increased confidence will be gained in the TASTEF and procedures used to date, achieving end-to-end testing.

LAR Evaluation

F/A-18 R_{max} and R_{min} were accessed at varying launch conditions. At each launch condition aspect angle was incremented by 5 degree intervals from 0 degree to 180 degree, rather than 0 degree to 360 degree. The LAR envelope was assumed to be symmetrical about the 0 degree/180 degree aspect axis, thereby reducing processing by a factor of two. An area in a horizontal plane was computed between R_{max} and R_{min}. This area constituted the basis for a LAR comparison. The launch condition, R_{max}, R_{min}, and resultant area were stored for comparison similar to that done in the ballistic mechanization evaluation. Of interest will be the percent of lost missiles (F/A-18 R_{max} greater than true R_{max}), percent of missed opportunities (F/A-18 R_{max} less than true or F/A-18 R_{min} greater than true), and percent of unsafe launches (F/A-18 R_{min} less than true R_{min}). At this time, the LAR analysis is incomplete.

A sensitivity study is planned for the LAR mechanization similar to that done on the A/G weapon delivery system. Sensor inputs to the LAR calculation will be perturbed and the resultant LAR area difference will be evaluated. This analysis will determine those sensors which most affect the calculation of R_{max} and R_{min}.

Summary

NAVAIRTESTCEN developed the TASTEF, not to replace flight testing, but to provide an affordable alternative to the costly process of collecting flight test data. By thoroughly examining the airplane/weapon system envelope with the TASTEF, the project engineer can identify those portions of the envelope which are critical and likely to yield deficiencies. These areas may then be used to develop a better flight test plan. In this manner, TASTEF helps to reduce wasted flights while increasing the engineers confidence in the data he collects.

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SIMULATION: THE BENCHMARK FOR AVIONICS LABORATORY INTEGRATION AND FLIGHT TEST

R.E. RYAN*

Northrop Corporation, Aircraft Division
One Northrop Ave.
Hawthorne, Calif.

ABSTRACT

This paper discusses the use of simulation during the testing and integration of navigation and weapon delivery avionics on high performance aircraft. During the avionics integration process, simulation models will be used to represent the environment, avionics functions and aero performance. These models will form a software functional representation of the aircraft flight parameters, "out of window" displays and avionics equipments. During flight test, avionics data will be recorded on the test aircraft and played-back into selected portions of the laboratory simulation configuration. These data will be used to re-construct the avionics aspects of the mission and provide inputs for post-test data reduction. While the testing facilities and techniques described herein are generic for advanced avionics testing, the thrust of this paper is their application to testing and integration of F-5G avionics. The site for the described F-5G and other avionics testing is the Northrop Avionics Integration Laboratory, located in the Aircraft Division Technical Center, Hawthorne, Calif.

BACKGROUND

Simulation will be used in the laboratory integration of advanced aircraft avionics by establishing a testing benchmark for subsequent testing. This benchmark will be composed of simulation software models that match the actual avionics components in terms of functional capability and interface. Other simulation models will be used to provide "out-of-window" displays and simulate aero and environmental parameters. During the laboratory integration process, various combinations of avionics components will replace simulation models. Finally, the test configuration will contain as much of the actual airborne avionics as can be cost-effectively tested in the laboratory. During aircraft avionics ground and flight tests, the laboratory simulation benchmark will be used to play-back selected data for post-test analysis and isolation of problems.

THE NEED FOR SIMULATION IN THE INTEGRATION PROCESS

Simulation allows a laboratory benchmark, or standard, to be established. The benchmark consists of the simulation software, standard test cases and test data. This benchmark is invaluable in testing the actual mission software and hardware and isolating problems during the integration process. A known and well tested simulation gives the testing agency a good reference from which to proceed. In addition, there are several of the actual airborne systems which cannot be fully tested in the laboratory. These systems have to be simulated to achieve the goal of a laboratory benchmark with good fidelity.

During integration testing in the laboratory, the simulation benchmark will be the "fall-back" reference point that test engineers can revert to when there are problems. A typical test scenario will be to interface one or more actual avionics units with a configuration consisting of simulated units. Operating characteristics of the simulation modules will be known, as well as expected performance of the unit(s) under test. Under this set-up, assuming that the benchmark has been correctly implemented, the ability to diagnose and trouble-shoot system problems related to the unit under test will be enhanced.

After flight test, recorded data from airborne units can be input to the simulation configuration to re-construct selected portions of the flight test.

AVIONICS INTEGRATION LABORATORY FUNCTIONS

The Northrop Avionics Integration Laboratory is presently being configured to perform the following functions:

a) Real-Time Flight Simulations - Simulate the flight of high performance aircraft in fixed-cockpit simulators. Included are non-combat functions such as flight control, navigation, mission planning, fix-taking and controls and displays. Combat functions include Air-to-Air and Air-to-Ground weapon delivery. While these functions are being performed, laboratory software simulates the environment, air-frame and selected Avionics Line Replacement Units (LRU's)

b) Avionic Unit Modeling - All of the major avionic LRU's will be modeled for laboratory simulation; these include:

   a) Multi-Mode Radar
   b) Inertial Navigation Unit
   c) Communications Navigation Identification Interface Unit
   d) Pylon Interface
   e) Heads Up Display and Heads Down Display
   f) Armament Control Panel
   g) Display Processor
   h) Missile Interface Units
   i) Mission Computer
   j) Flight Control Electronics System

*Manager of Avionics Systems Test, Avionics Engineering

k) Air Data Computer

The simulations are resident on laboratory VAX 11/780 systems.

c) Software Development - This development includes all of the software necessary to run the laboratory, ie., maintenance of VAX system software, graphics package and generic simulation software. Also included are utility routines, data reduction programs, test support software etc.

d) Avionic Sub-System Tests - A laboratory test fixture is being built for each major avionic LRU. Sub-system testing will be conducted to verify proper "stand-alone" operations of the LRU and the units ability to communicate with the 1553 bus.

e) Integration Tests - Integration testing will include two or more avionic models or LRU's functioning together while interfaced to the 1553 bus. Initial testing will be performed using test software. Advanced or avionic system testing will be performed using mission software and flight scenarios.

f) Operational Flight Program (OFP) Development and Test - This includes the development, module and system integration testing of flight software.

LABORATORY HARDWARE CONFIGURATION

Generically, the Avionics Integration Laboratory provides three VAX 11/780 systems, mini-computers and other peripherals, graphics systems, test stations and equipment, multi B-byte storage and two cockpits for a variety of advanced avionics testing and integration projects.

For real-time support, the laboratory utilizes dual VAX 11/780's with an MA Shared Memory. This configuration includes 3.75 mega-bytes of memory for each processor and .25 mega-bytes of shared memory. Disk storage is about one B-byte. The system includes two terminal ports, four printers and two magnetic tape drives.

Peripheral hardware includes the cockpits, Evans and Sutherland Multi-picture Systems, five PDP-11/23's and one PDP 11/60.

Figure 1 depicts the above configuration.

Figure 2 shows the relationship of the equipment to the development, test and evaluation phases of F-5G avionics integration. Note on Figure two that one VAX 11/780 and one set of peripheral equipment is dedicated to F-18L simulation work. The purpose of this configuration is to support F-18L study and demonstration work being performed in the Integration Laboratory.

In addition, the F-5G laboratory configuration includes a VAX 11/780 for non-real-time support. This VAX is dedicated to software development and configuration control, documentation and general purpose processing. Included in this system are 3.75 mega-bytes of memory and .75 B bytes of disk storage, 48 operator terminals three printers and one magnetic tape drive.

F-5G AVIONICS SYSTEM

Figure 3 is a block diagram of the F-5G avionics system. This system is typical of the types of advanced avionics that can be tested in the Avionics Integration Laboratory. Following is a brief description of each of the major components:

A) MIL-STD-1553B BUS

This is a dual multiplex bus used as the prime interface between each of the avionics components. Data traffic on the bus is at a 1 MHz rate and is controlled by the Mission Computer.

B) HEADS-UP-DISPLAY (HUD)

This is a display in front of the pilot which projects selected flight and fire control parameters on the "real-world".

C) FLIGHT CONTROL ELECTRONICS SYSTEM INTERFACE (FCES)

This unit interfaces through the Air Data Computer to the multiplex bus.

D) MISSION COMPUTER

This unit is the bus controller. The Operational Flight Program (OFP) resides in this computer. In addition to bus control, the OFP also provides calculations for navigation, controls and displays, mission planning, fix-taking, self-test and weapon delivery.

E) COMMUNICATIONS NAVIGATION IDENTIFICATION INTERFACE UNIT (CNIIU)

The CNIIU interfaces miscellaneous communications, navigation and identification units to the multiplex bus.

F) INERTIAL NAVIGATION UNIT (INU)

The INU provides real-time aircraft state vector (position, velocity and acceleration) information for navigation and weapon delivery.

G) COHERENT RADAR

This is a multi-mode airborne radar system capable of airborne target detection or ground mapping.

H) DISPLAY PROCESSOR

The Display Processor performs calculations necessary to place displays on the Digital Display Indicators (DDI's) and HUD.

I) ARMAMENT CONTROL PANEL (ACP) AND STORE STATIONS

These units control the delivery of weapons and provide for stores jettison.

REAL TIME SIMULATION CONFIGURATION

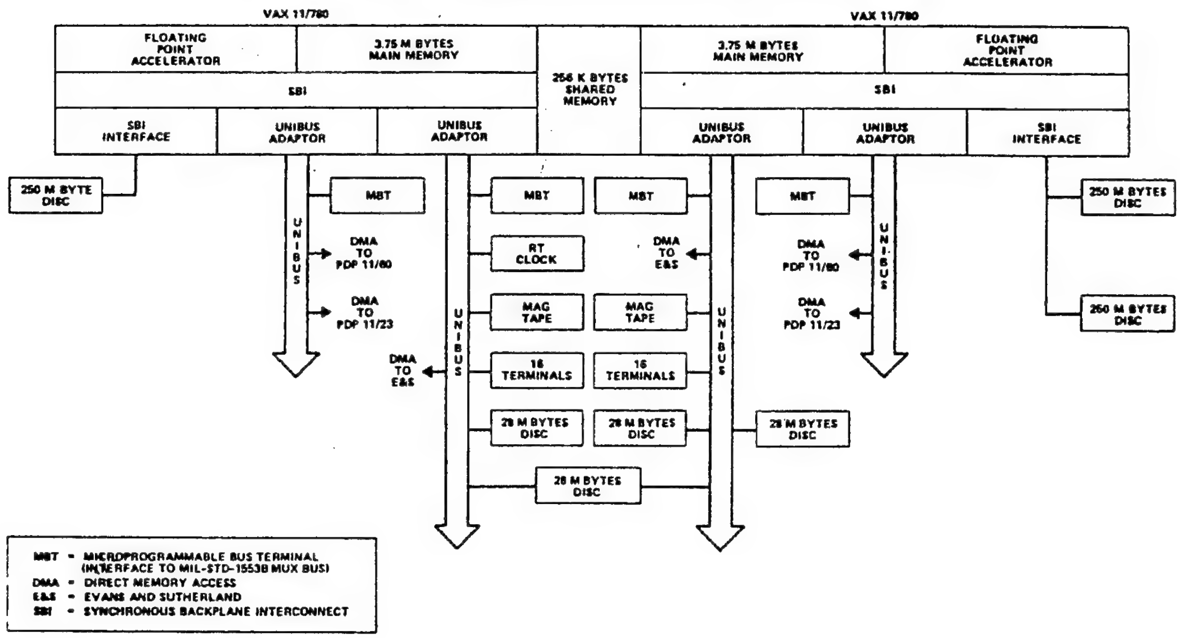

FIGURE 1

INTERPROCESSOR RELATIONSHIP

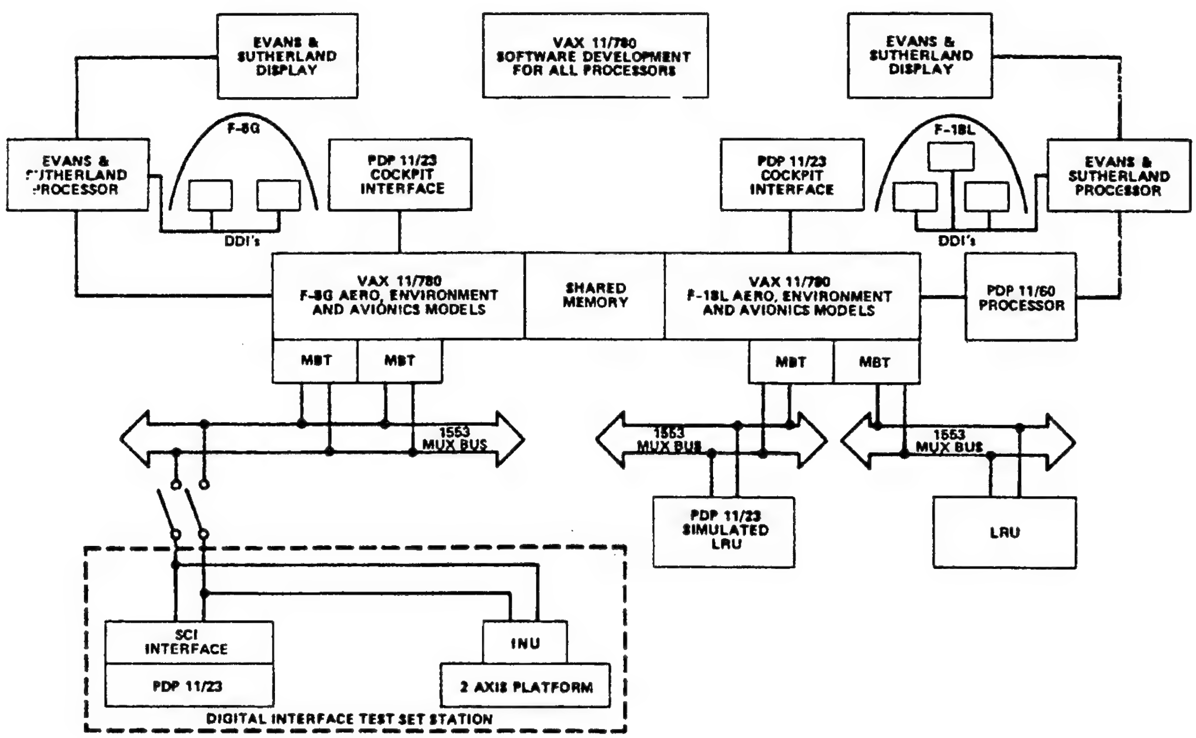

FIGURE 2

F-5G AVIONICS SYSTEM

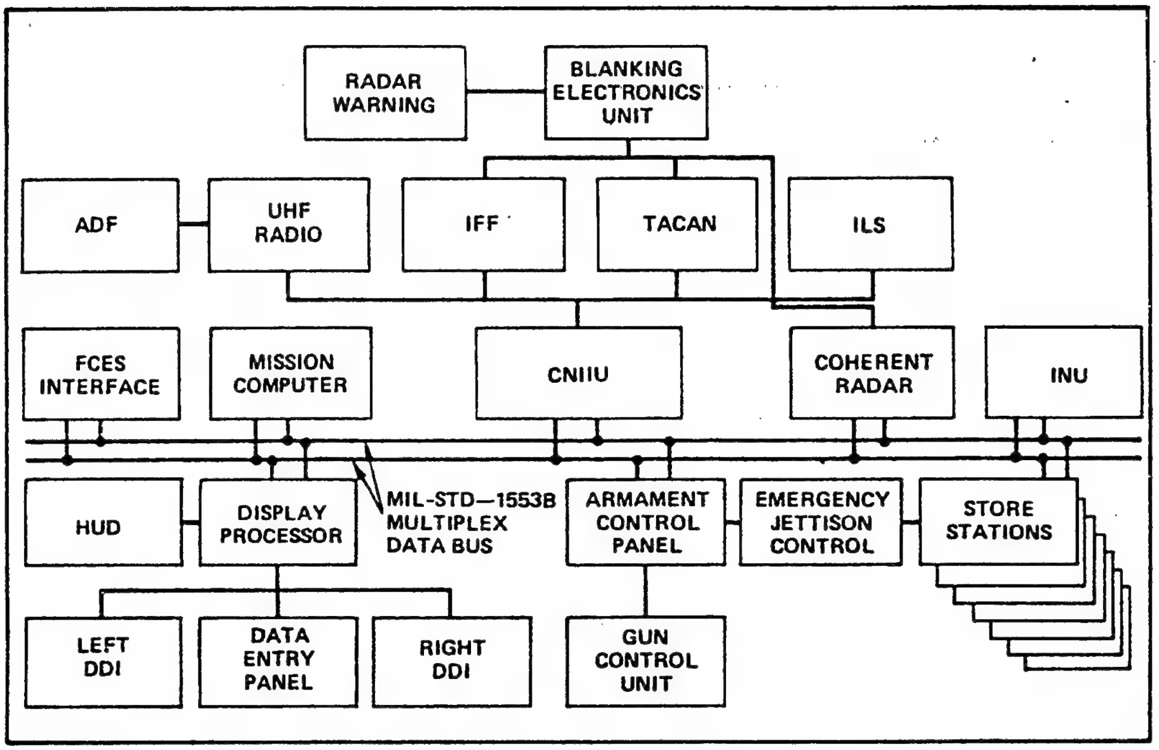

FIGURE 3

GOALS OF THE AVIONICS INTEGRATION PROCESS

The prime purpose of the laboratory integration process is to functionally test the fighter avionics prior to installation of the system on the test aircraft. After ground and flight testing begins, an additional role of the laboratory will be to evaluate flight test data and provide resolution to problems that are detected in the air. Specifically, the goals of F-5G Laboratory Integration Testing are to:

a) Functionally test the system comprising F-5G avionics hardware and software in a laboratory environment. Test the various hardware and software interfaces in the system. Provide the capability to "fly" typical flight scenarios in the laboratory. Perform as much testing in the laboratory as possible to conserve valuable test aircraft flight time.

b) Provide a test bed for the resolution of problems which occur during avionics ground and flight tests.

c) Provide fixed cockpit simulators to resolve man-machine, switchology and display symbology problems.

d) Provide the capability to play-back aircraft test data into the simulation benchmark configuration for post-flight evaluation.

F-5G SIMULATION MODELS

Simulation software models, resident in the VAX 11/780 systems, will simulate avionics units and generic functions, such as earth, atmosphere and graphics. Other models will simulate aero functions such as propulsion, flight control, air data etc. Figure 4 is a block diagram of the interaction between the simulation models resident in the VAX systems, the hardware test stations, MIL-STD-1553 bus, the cockpit and avionic unit(s) under test. Following is a brief description of each of the avionic simulation models:

a) Multi-Mode Radar - This simulation will include generation of target video, which will be injected into the radar after the signal processor.

b) Inertial Navigation Unit - This simulation will provide state vector (position, velocity and acceleration), true and magnetic heading, roll, pitch, yaw,

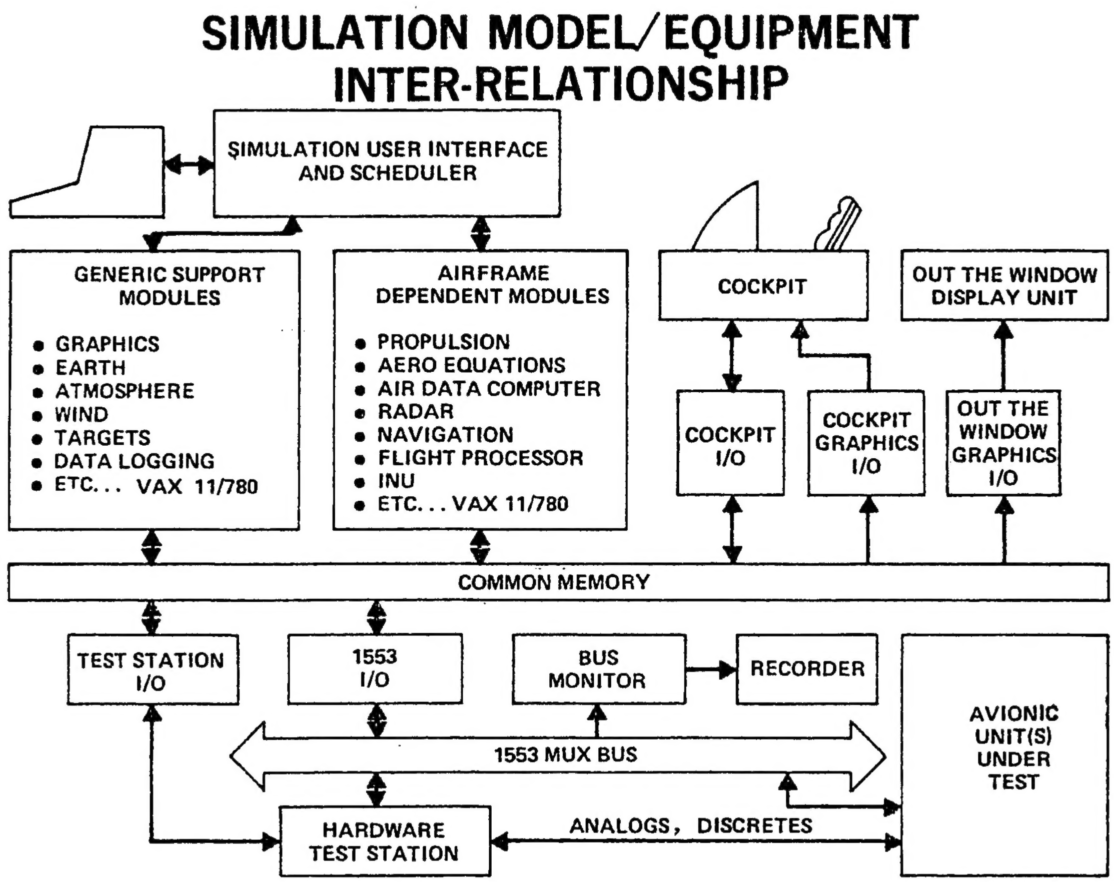

FIGURE 4

latitude, longitude, drift, track and wind angles and bearing. Also included will be the back-up 1553 multiplex bus control function.

c) Communications Navigation Identification Unit - This model will simulate interface of the 1553 bus to the UHF Receiver, ILS Receiver, IFF Transmitter, TACAN, Directional Gyro and ADF.

d) Pylon Interface Unit - Simulates pylon interface to the aircraft and stores release.

e) Missile Interface Unit - Simulates missile interface to the pylon and stores release.

f) Heads-Up-Display - Provides presentation of fixed depressed reticle, pitch ladder, flight parameters, gun aiming symbols, variable coordinates and other pilot presentations.

g) Heads-Down-Display - Provides radar video, missile video, pilots data entry panel and selected digital data.

h) Armament Control Panel - Simulates hands on stick and throttle, stores jettison and interface between cockpit and pylon.

i) Display Processor - Simulates man-machine interface between pilot and avionics, avionic sub-system status and provides format and symbol generation.

j) Mission Computer - Simulates the mission control functions: bus control, executive, weapon delivery and navigation calculations, mission data entry, display format control, system initialization and shut down and other control functions.

k) Flight Control Electronics System - This model simulates propulsion control, stability augmentation, two axis digital surface control and auto flaps.

l) Air Data Computer - Provides altitude and altitude rate, Mach number, calibrated air speed, true air speed, angle of attack and relative air density.

LABORATORY INTEGRATION OF AVIONICS SYSTEMS USING SIMULATION TECHNIQUES

The simulation models described above are the key ingredient in setting up a testing laboratory for hardware/software integration purposes. The aero, environmental and equipment software models, along with test case data, form a software laboratory benchmark which can be used as a standard to test the actual flight hardware and software. In fact, the first integration effort in the Northrop Avionics Integration Laboratory will be to integrate the various software simulation models. The models will reside in the VAX 11/780 processors and will be tested against typical scenarios so that the baseline characteristics of models will be known. Test cases for avionic models will be developed, taking the equipment specifications into consideration.

As the simulation benchmark is being developed, a parallel effort of building avionic equipment tests stations is being undertaken. These test stations will include holding fixtures for the avionic equipment and interfaces for power, test equipment and the 1553 multiplex bus. Test equipment and test stations will involve a Digital Integration Test Set (DITS) and an Avionic Integration Development Station (AIDS). The DITS will provide stimulation signals to avionic test configurations. The AIDS will provide test engineer interface to the test configuration. Included will be simulation, cockpit and Performance Monitor terminals, cockpit controls, "Out of Window" and Digital Data Indicator displays and support hardware.

During testing of the avionic sub-systems, the DITS and other test equipment will stimulate the avionic sub-system under test to ensure that it functions according to specifications and will interface with the 1553 bus. In addition, the mission software will be undergoing integration testing.

As the avionic equipment and mission software complete sub-system and module testing, they become candidates for integration testing. During integration, each sub-system and block of mission software is interfaced to the 1553 bus and subjected to a series of functional system tests. These tests will verify functional compatibility of each sub-system with each of the other sub-systems or simulation models interfaced to the multiplex bus. Figure 5 depicts the test flow sequence beginning with vendor acceptance test through system level tests in the integration laboratory. In this graphic, the testing relationship of simulation models, 1553 bus, units under test, DITS, AIDS and cockpits is shown.

During integration testing, performance

AVIONICS INTEGRATION LABORATORY TEST FLOW SEQUENCE

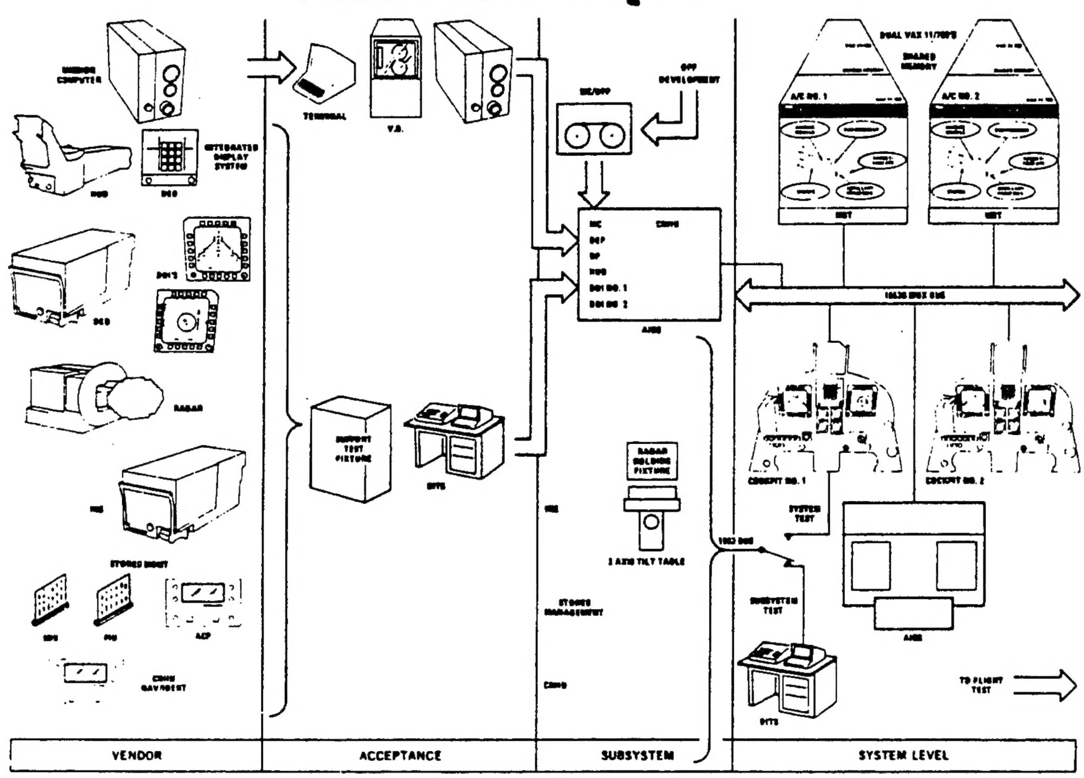

FIGURE 5

against the avionics system "A level" specification is verified to the extent practically possible in a laboratory test environment.

Mission scenarios during system integration test will include:

a) Navigation - Verification of the navigation accuracy specifications and radar target processing.

b) Air-To-Air Weapon Delivery

c) Air-To-Ground Weapon Delivery

d) Compatibility Tests to verify compatibility of the avionic subsystems, the 1553 bus and the Mission Software.

MISSION SOFTWARE TEST

The mission software is being written in J73 Jovial language and will reside in a MIL-STD-1750A processor on the F-5G aircraft. The Jovial source code will be micro-waved from the Avionics Integration Laboratory to the Northrop Computer Center via a micro-wave link. There, the source code will be compiled, micro-waved back to the laboratory and downloaded from the VAX to the Mission Computer. Then, the mission software will undergo testing (module or system integration). Figure 6 is a flow diagram of this process.

SIMULATION AS AN AID TO FLIGHT TEST EVALUATION

The Integration Laboratory will be an integral part of evaluating data from aircraft avionics ground and flight tests. A full set of 1553B multiplex bus data will be collected on the test aircraft during avionics flight tests. These data will be re-formatted and played-back into the laboratory simulation benchmark, so that selected portions of airborne missions can be re-constructed and "flown" in the laboratory. This will allow for:

a) Functional evaluation of the Avionics

b) Isolation of problems in the laboratory

c) Evaluation of Man-machine interfaces

d) Symbology and switchology evaluation

In addition, avionics flight test data will be reduced by data processing software so that a qualitative evaluation of avionics system flight performance can be made.

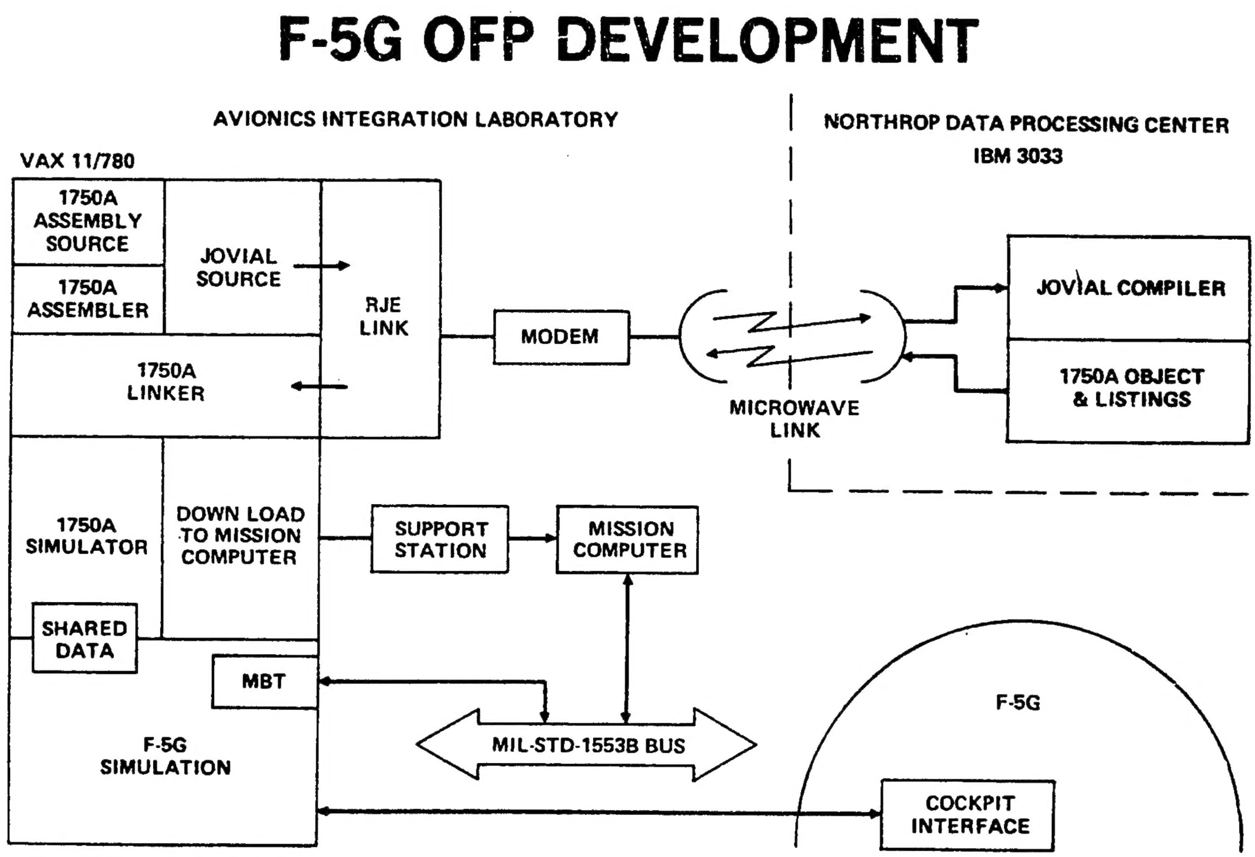

FIGURE 6

FLIGHT TEST DATA SYSTEM

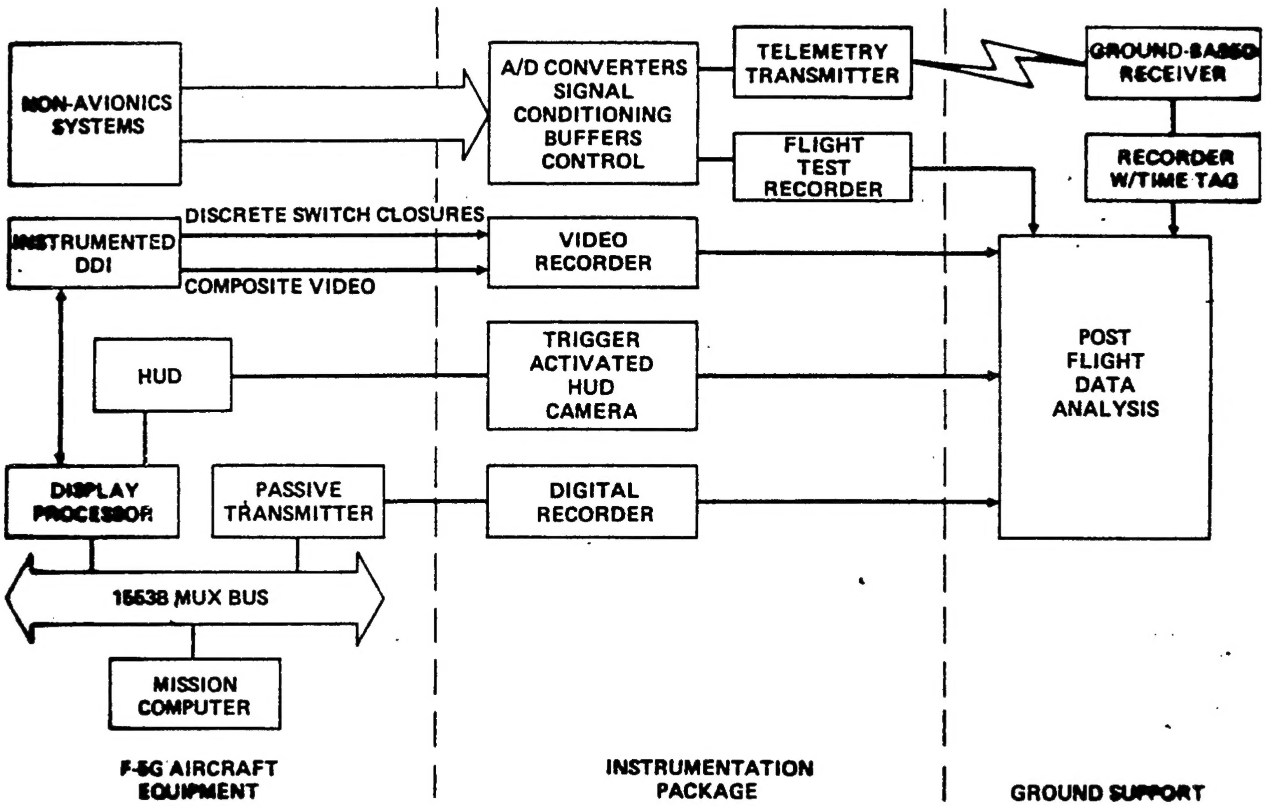

FIGURE 7

Figure 7 is a block diagram of the airborne data acquisition system on the F-5G and supporting ground functions. Acquisition and reduction of non-avionics telemetry data consists of a standard system: signal conditioning, buffering into a telemetry transmitter and recording on a MARS 2000 Flight Recorder. The telemetry down-link is used for real-time quick look analysis and the reduced flight tapes provide a print-out of flight performance parameters.

Three types of avionics data will be recorded on the F-5G: (1) Digital Data Instrument (DDI) pilot switch hits and composit video (information and symbols); (2) Total 1553 bus traffic; (3) Heads-Up-Display (HUD) camera. During data reduction, these data will be processed to provide avionic performance evaluation data. In addition, this data set will allow flights to be re-constructed in the laboratory, using selected portions of the simulation benchmark as a standard.

Mission re-construction in the Integration Laboratory will allow a complete performance evaluation of avionics data from each flight test. Mission-to-mission performance of the avionics hardware and software and the systems response to pilot and mission computer commands will be known. This will be invaluable during the trouble-shooting of problems which occur in the air.

CONCLUDING REMARKS

The Northrop Avionics Integration Laboratory is being configured to support the integration and evaluation of F-5G avionics from the initial sub-system tests through flight testing. All avionics hardware and software will be thoroughly tested in the laboratory prior to installation on the test aircraft. After flight testing begins, a full set of avionics mission data will be acquired on each test flight. These data will be used to support post-test data processing, mission re-construction, anomaly investigations and performance evaluation. The goals of this approach are to:

a) Provide a tested and integrated avionics system to the F-5G test aircraft for flight testing.

b) Provide test engineers the data and analysis tools they need to evaluate flight tests.

c) Reduce the turn-around time in identifying flight problems, solving them and re-testing. This will significantly minimize the cost and schedule impact of avionics flight test problems.

The Avionics Integration Laboratory hardware will be configured and simulation software development completed in 1982. Data reduction software development will be completed and avionics sub-system testing will begin in early 1983.